LBNE Near-Detector

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Questions regarding the PMNS Matrix Elements

- Θ_{13} Sensitivity
- δ_{CP} Sensitivity
- ν-Mass Hierarchy
- Resolving degeneracies

⇒ Need Syst.Precision

(Nu -vs- NuBar ⇐ δ_{CP})

Beyond PMNS

- Θ_{23} = 45^0 ?
- CPT Violation ?
- High Δm**2 Oscillation ?
- Phenomenon that defies the Zeitgeist

The familiar, beautiful neighborhood

- X-secs, Sin**2(Θ_W): precision comparable to Colliders?
- Sum rules, Isospin Physics (Nu -vs- NuBar ⇐ δ_{CP})
- Heavy neutrinos
- ....
- Rewriting the ν text-book

Reinventing the Near Detector

✦ *Use of "identical" small detector at the near site is insufficient for future $\mathcal{LBL}$ experiments:*

- $\Phi^{\nu,\bar{\nu}}(E_\nu, \theta_\nu)$ *different at Near & Far sites;*
- *Impossible to have "identical" detectors, for $\mathcal{O}(100kt)$, at the projected luminosities;*
- *Different compositions of event samples ($\nu_\mu, \bar{\nu}_\mu, \nu_e$, NC, CC)*

$\Longrightarrow$ *Coarse resolution dictated by $\mathcal{O}(100kt)$ and different flux at Near-vs-Far tell us that the Identical Near Detector concept is insufficient*

✦ *Need a high resolution detector at the Near-Site to measure systematics affecting the Far-detector:*

- $\nu_\mu, \bar{\nu}$, $\boxed{\nu_e}$, $\boxed{\bar{\nu}_e}$ *content vs. E_ν and θ_ν;*
- ν*-induced $\pi^\pm/K^\pm/p/\pi^0$ in CC and NC interactions;*
- *Quantitative determination of E_ν absolute energy scale;*
- *Measurement of detailed event topologies in CC & NC.*

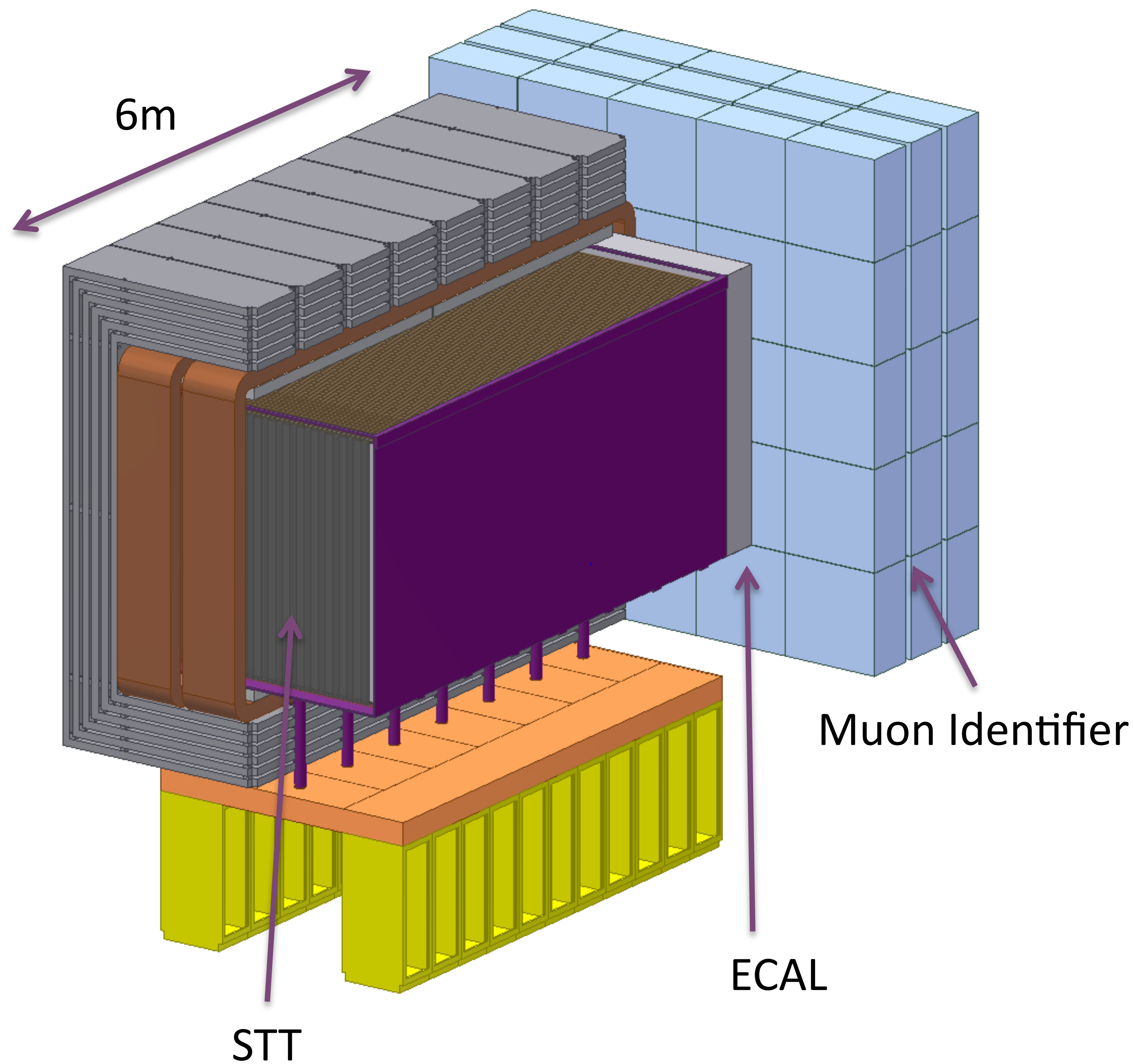
$\Longrightarrow$ *Provide an 'Event-Generator' measurement for $\mathcal{LBL}\nu$*

- Measure over the full range of FD
- Background to the ν(Bar)e/μ-Appearance
- ν -vs0 ν(Bar) Interactions

✦ *High Resolution near detectors at future $\mathcal{LBL}$ facilities are natural heirs to the precision neutrino scattering programme*

Can they achieve sufficient precision to complement the Colliders?

Straw Tube Tracker (STT)



- Best performance of the 4-options
- 3.5m x 3.5m x 7m STT (7 tons; $\rho \simeq 0.1 gm/cm^3$)

  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

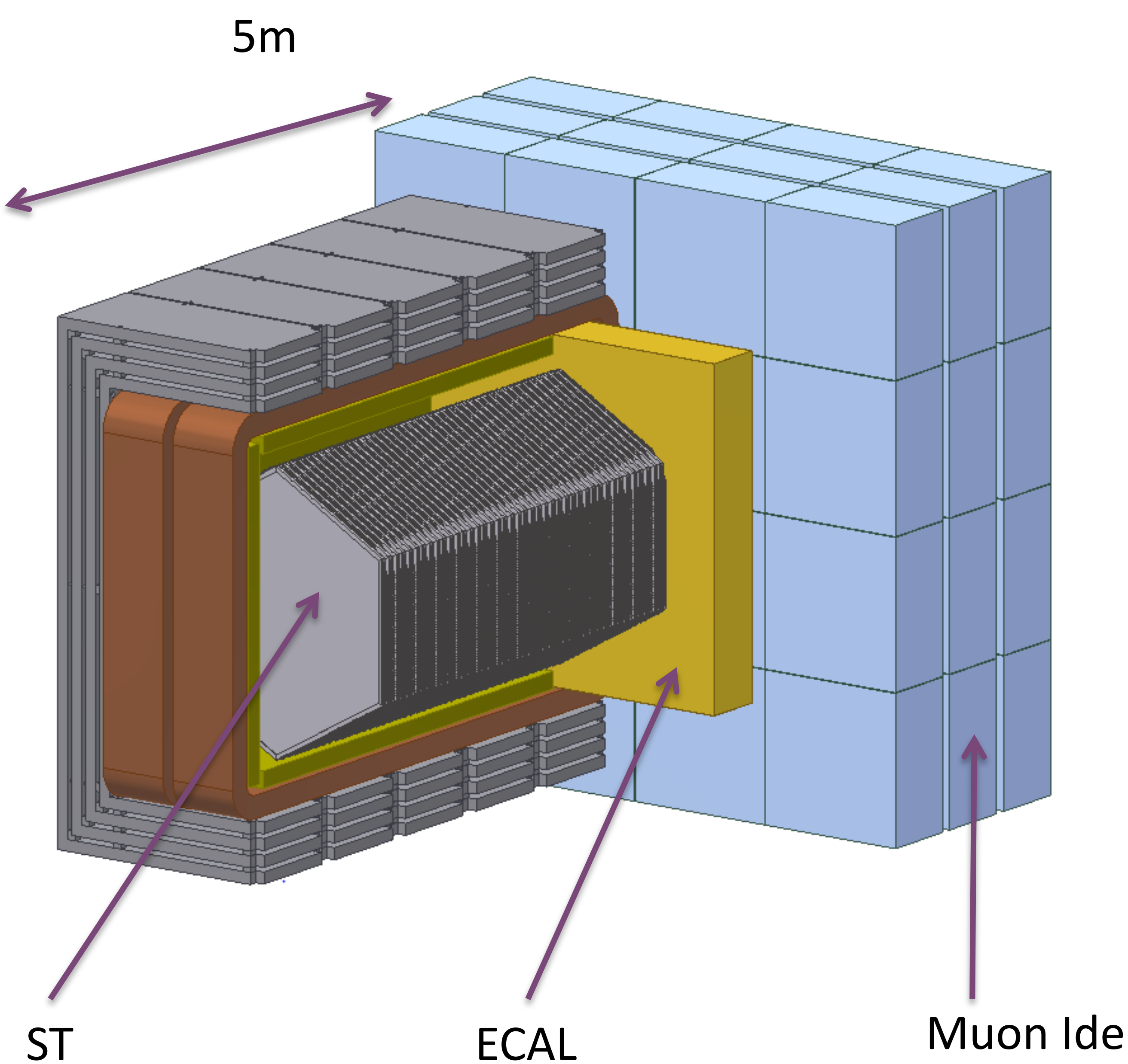
Transition Radiation	⇻ e-/e+ ID ⇒ γ
dE/dx	⇻ Proton, π+/-, K+/-
Magnet/Muon Detector	⇻ μ+/-

- H2O & D2O Targets (≃x5 FD-Stat) ⇛ *WC-FD*

  {QE-Proton ID ⇒ Absolute Flux measurement}

- Pressurized Ar-target (≃x5 FD-Stat) ⇛ *LAr-FD*

Scintillator Tracker (ST)

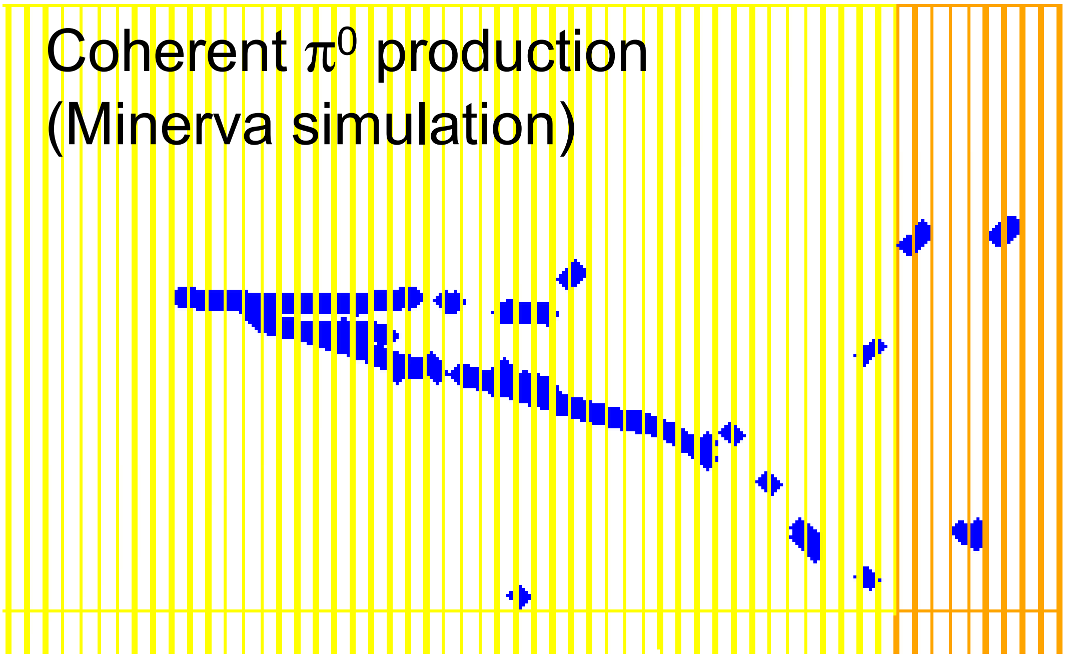


- 3m x 3m x 5m Sci-Tracker (7 tons; $\rho \simeq 1 gm/cm^3$)

  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

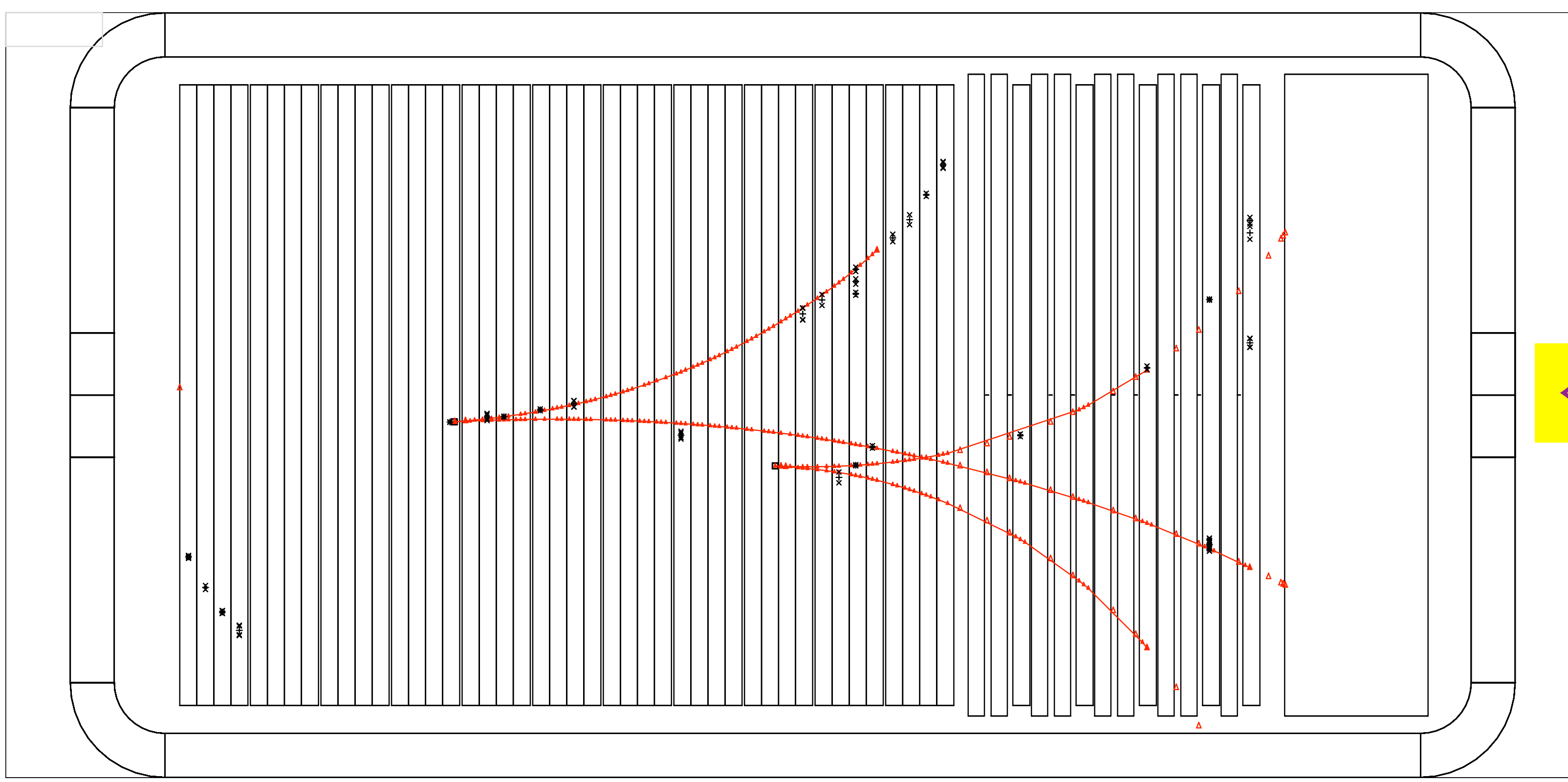
- H2O Target (≃x5 FD-Stat) ⇛ *WC-FD*

Coh-π0



A Question of Resolution...

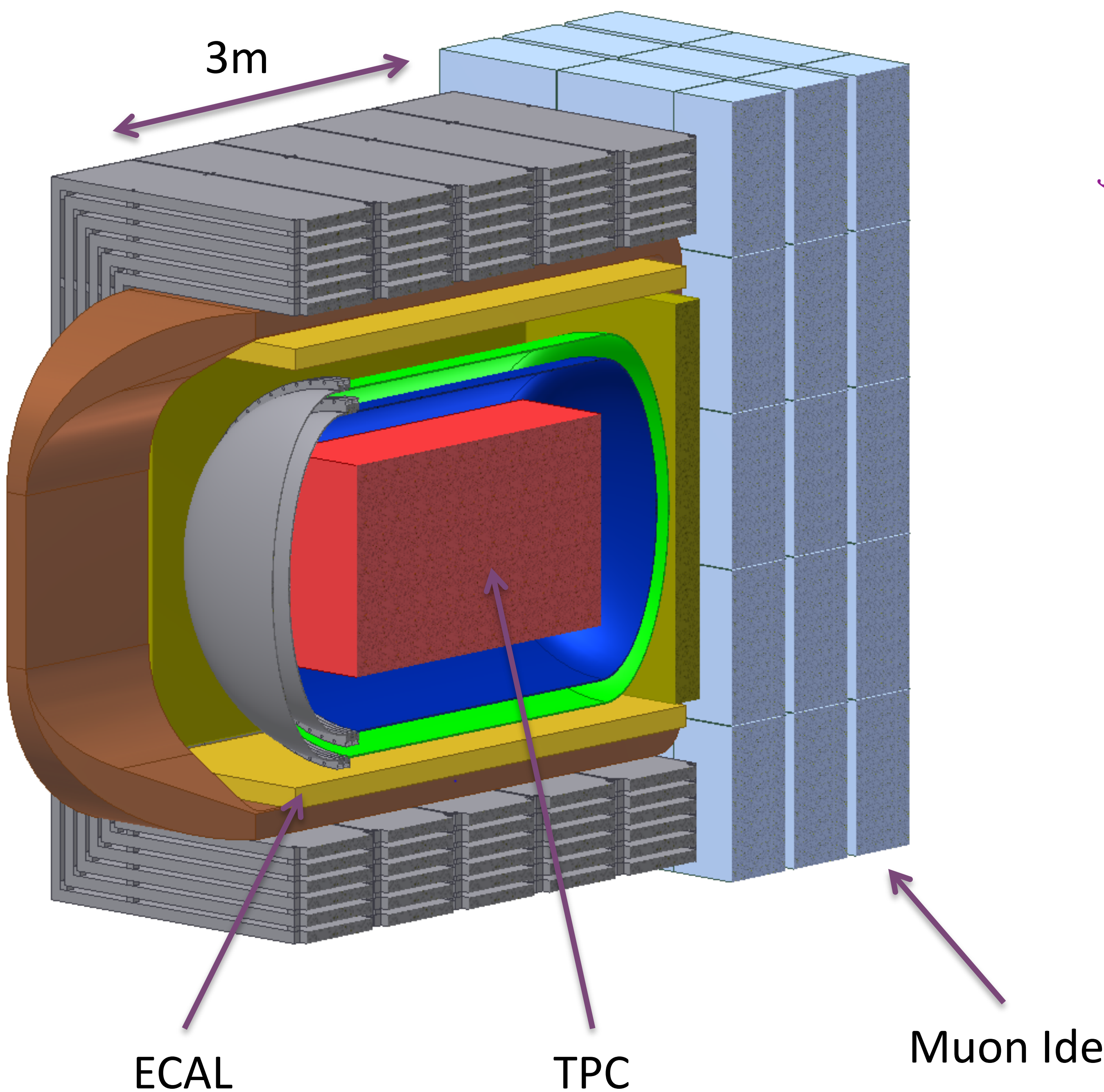
NOMAD DATA



⇐ x12 more hits in STT

(Hits shown by \`x' are not used in the track-fit)

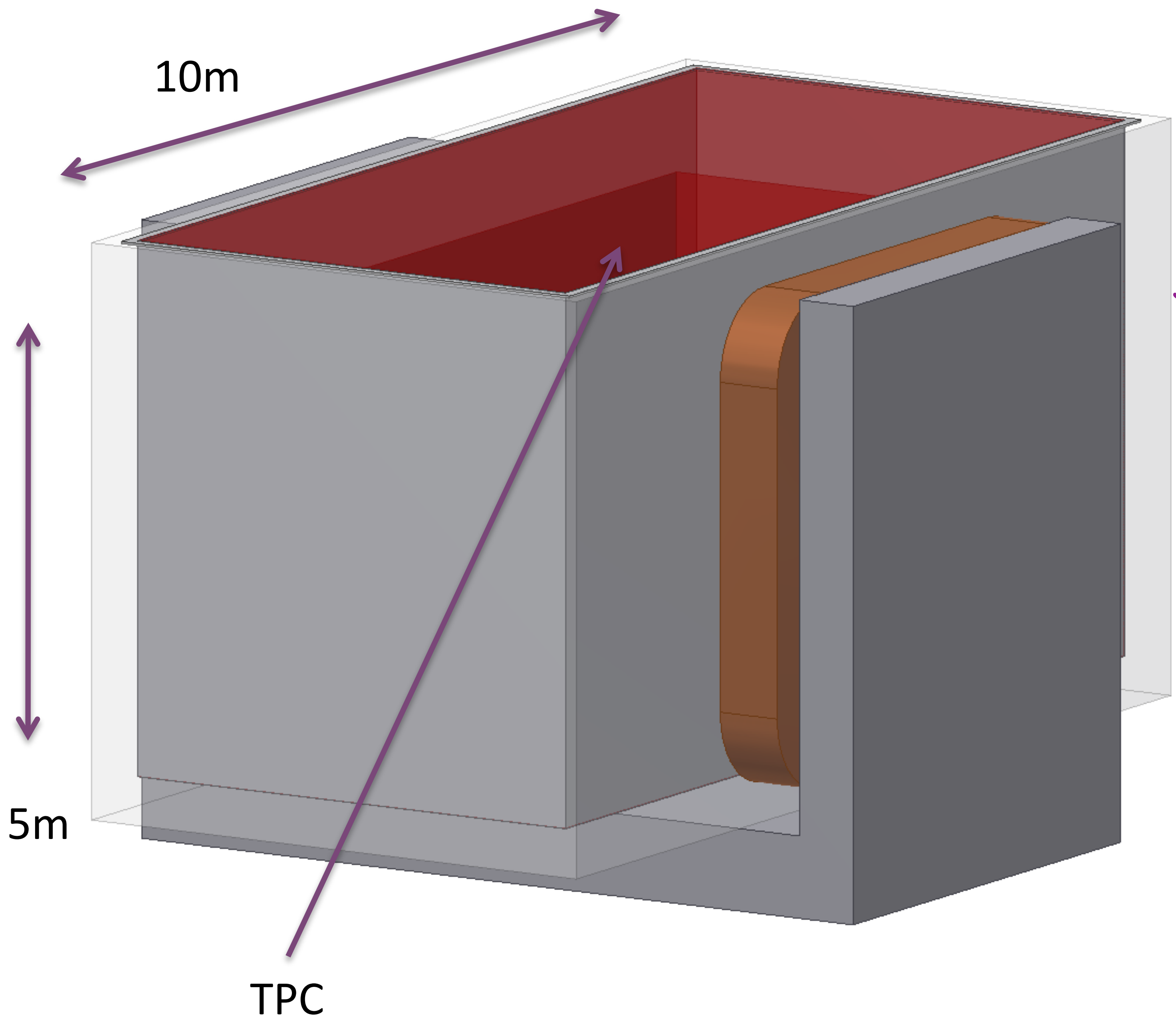
LAr TPC Tracker (TPCT)



- 1.8m x 1.8m x 3m LAr (13 tons)
  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

⇛ *LAr-FD*

Membrane LAr TPC (LArM)



- 5m x 5m x 10m LAr (350 tons)

  with membrane cryostat; B-Field (0.4T) ⇛ μ-Sign

⇛ *LAr-FD*

Why Tracker (ECAL/*μ-Detector*) within a B-Field?

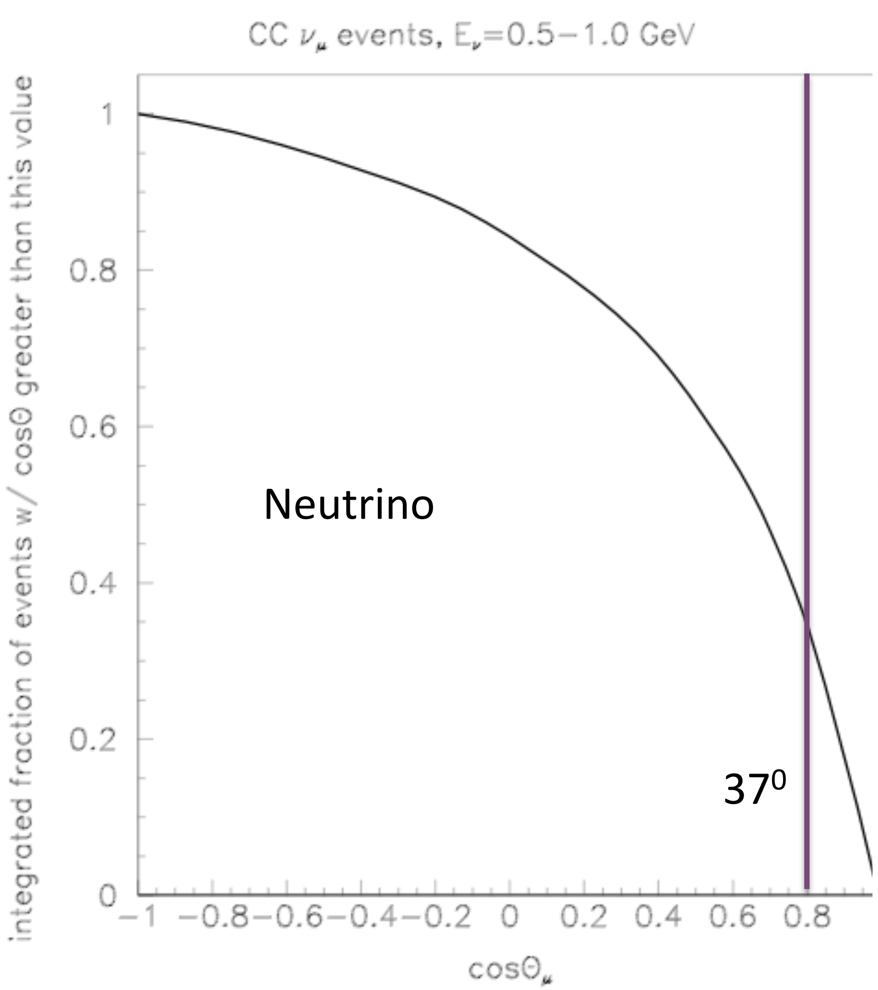
- Constrain $E\nu$-scale
- ND must measure the full range of $E\nu$ & $\theta\nu$ else the sensitivity of FD will be compromized
- In $0.5 \leq E\nu \leq 1$ GeV, the Acceptance $\simeq$ 35% for $\theta\mu \leq 37$^0

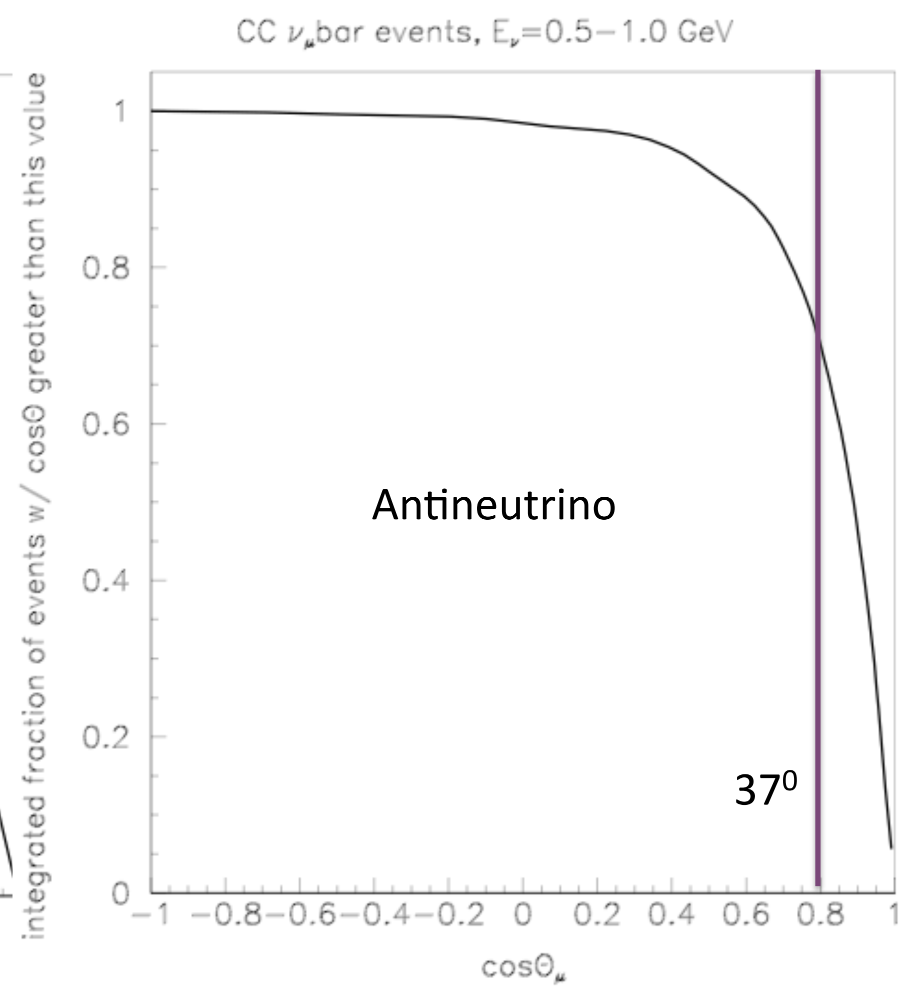
  In $2.0 \leq E\nu \leq 3$ GeV, the Acceptance $\simeq$ 75% for $\theta\mu \leq 37$^0
- For LBNE, the Maximal sensitivity for δ_{CP} is $E\nu \simeq 1.5$ GeV
- STT will be able to distinguish *μ-/μ+* down 0 ~0.3 GeV

$\Rightarrow$ *ND must measure and ID leptons (at least μ) emerging at large angles;*

Must measure differences in ν & Anti-ν *interactions which might fake a "* δ_{CP} *"*

0.5-1 GeV





Why track protons?

- Precision determination of ν_μ-QE requires proton-tracking.

⇒ QE in H_2O & D_2O will provide an Absolute-Flux measurement:

Need proton-tracking & resolution to point to the H_2O & D_2O vertex

⇒ (μ^-, p) provide an *in situ* constraint on the Fermi-motion and hence on the E_ν-scale

⇒ QE interactions dominant in Low-E_ν: Need accurate parametrization of QE

- STT option will have a large proton sample from $\Lambda \rightarrow p\pi$

- If an ND is able to accurately measure proton, it will be able to measure the π^- & π^+ in NC and CC:

the largest source of background to the ν_μ & *Anti-*ν_μ *disappearance*

⇒ *ND must track & ID QE-protons*

ν_μ-QE Sensitivity Calculation

- Example of a ν-interaction in a high-resolution ND as a calibration of FD

- Key is 2-Track (μ, p) signature *Proton reconstruction: the critical issue*
  (*dE/dx in but not used in the analysis*)

- Use Nomad data/MC as calibration

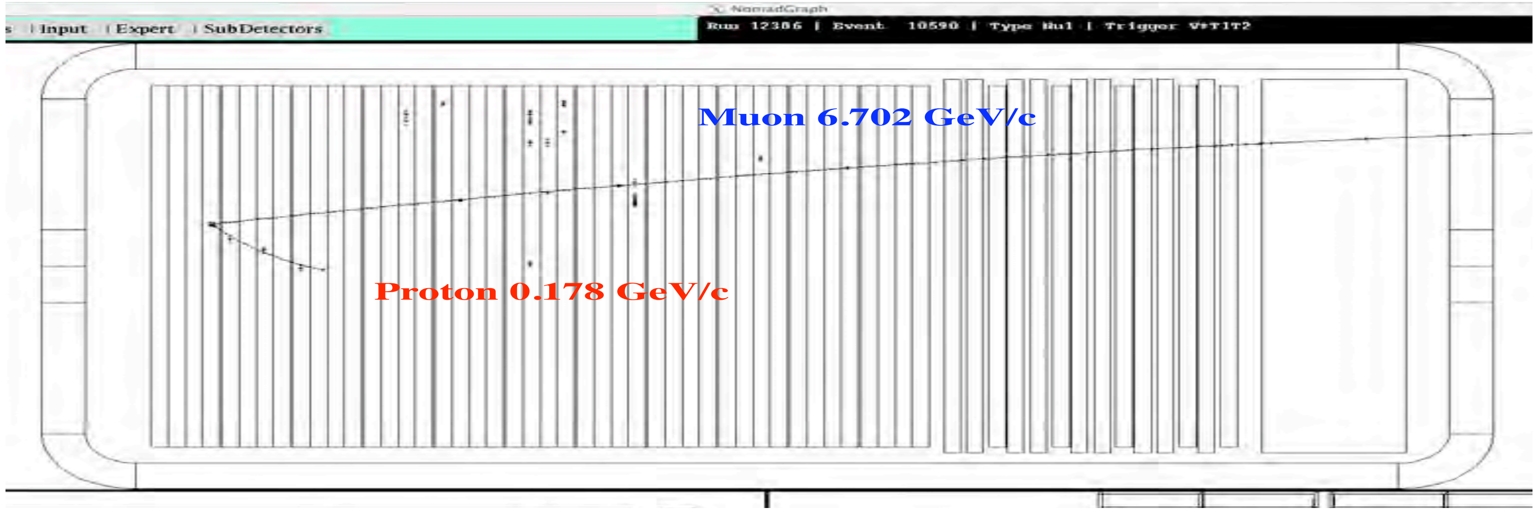


Figure 14: A ν_μ-QE candidate in NOMAD

QE Candidates in NOMAD: STT will have x6 more points for protons

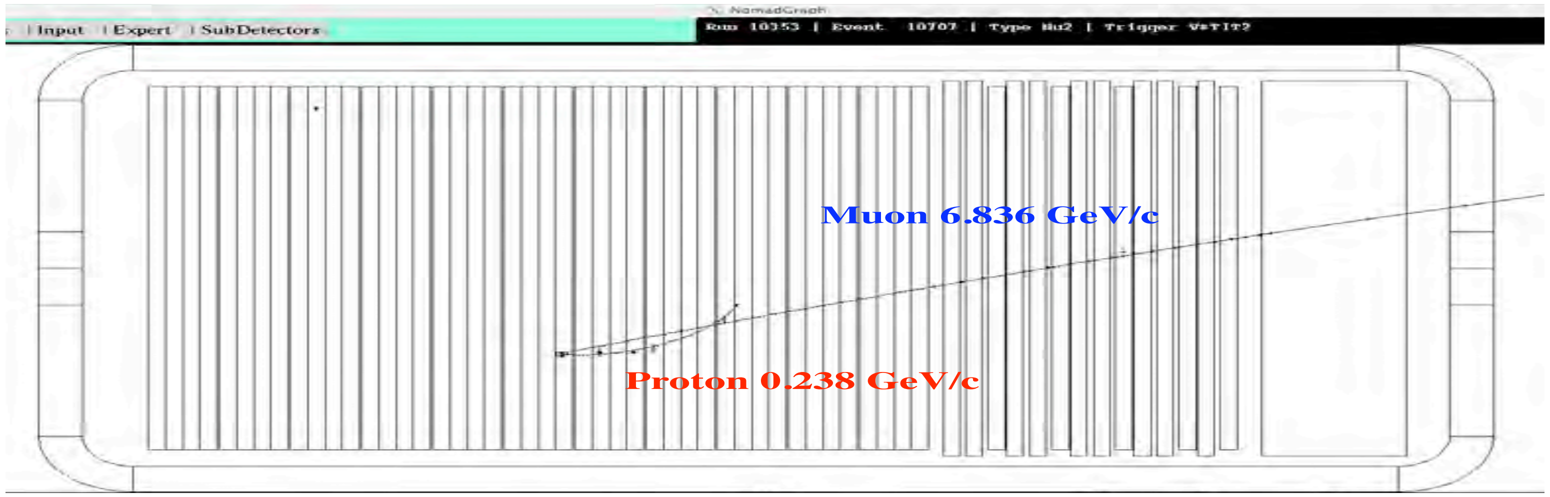
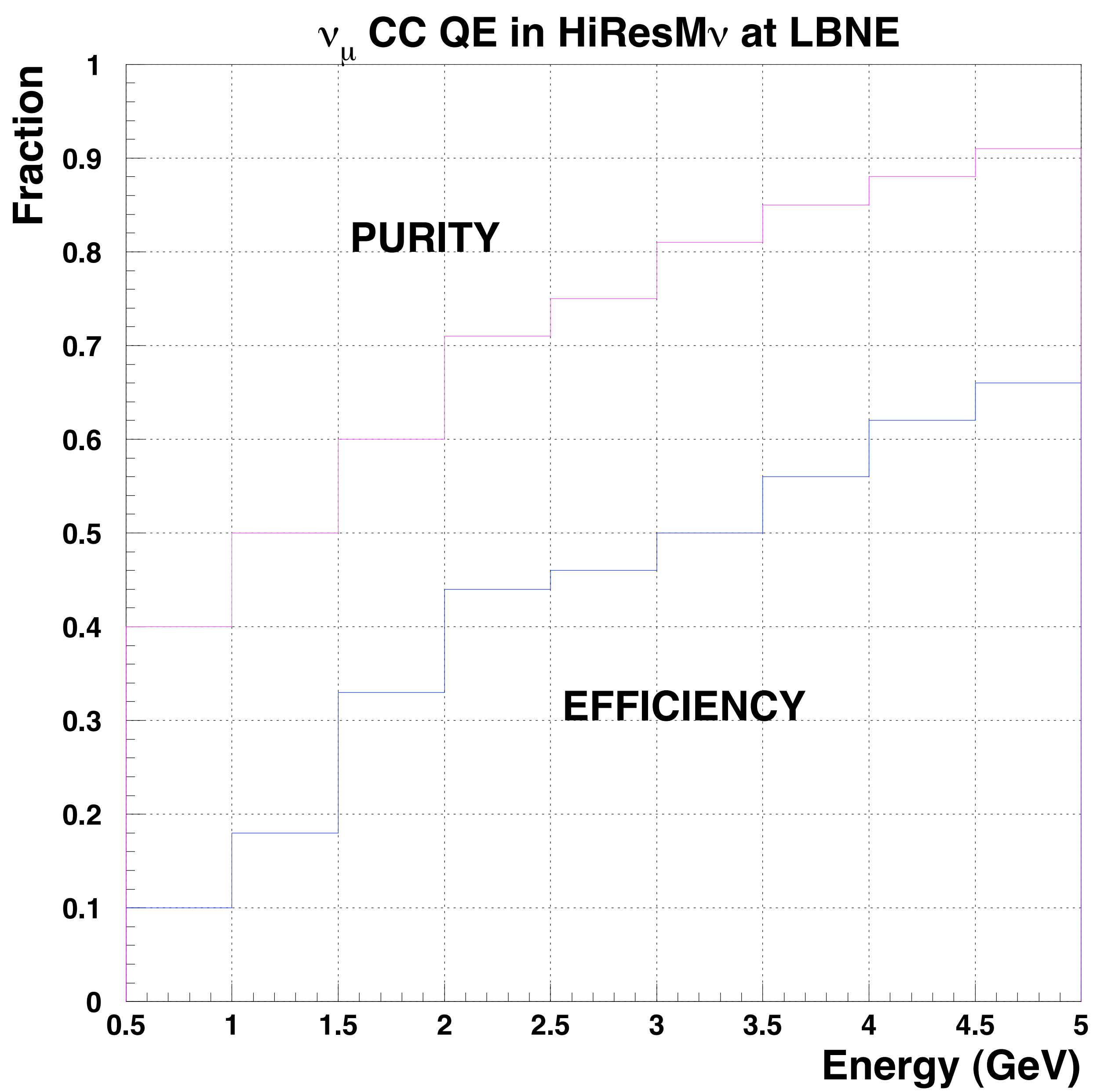


Figure 15: A ν_μ-QE candidate in NOMAD

RECONSTRUCTION OF CC QUASI-ELASTIC INTERACTIONS



- *Protons easily identified by the large dE/dx in STT & range*

  $\Longrightarrow$ *Minimal range to reconstruct p track parameters 12cm* $\Rightarrow 250\ MeV$

- *Analize BOTH 2-track and 1-track events to constrain FSI, Fermi motion and nuclear effects*

- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject DIS & Res backgrounds*

  $\Longrightarrow$ *On average* $\varepsilon = 52\%$ *and* $\eta = 82\%$ *for CC QE at LBNE*

Why measure and ID *e-* & *e+*?

- Measurement of π^0 in NC and CC via $\gamma \rightarrow e^-e^+$ measured in the tracker

{π^0 is the largest background to (anti)ν_e-appearance}

- Measure beam ν_e and Anti-ν_e

⇒ Difference between (ν_e from μ) & (anti-ν_e from K0L) extrapolations to FD from ND

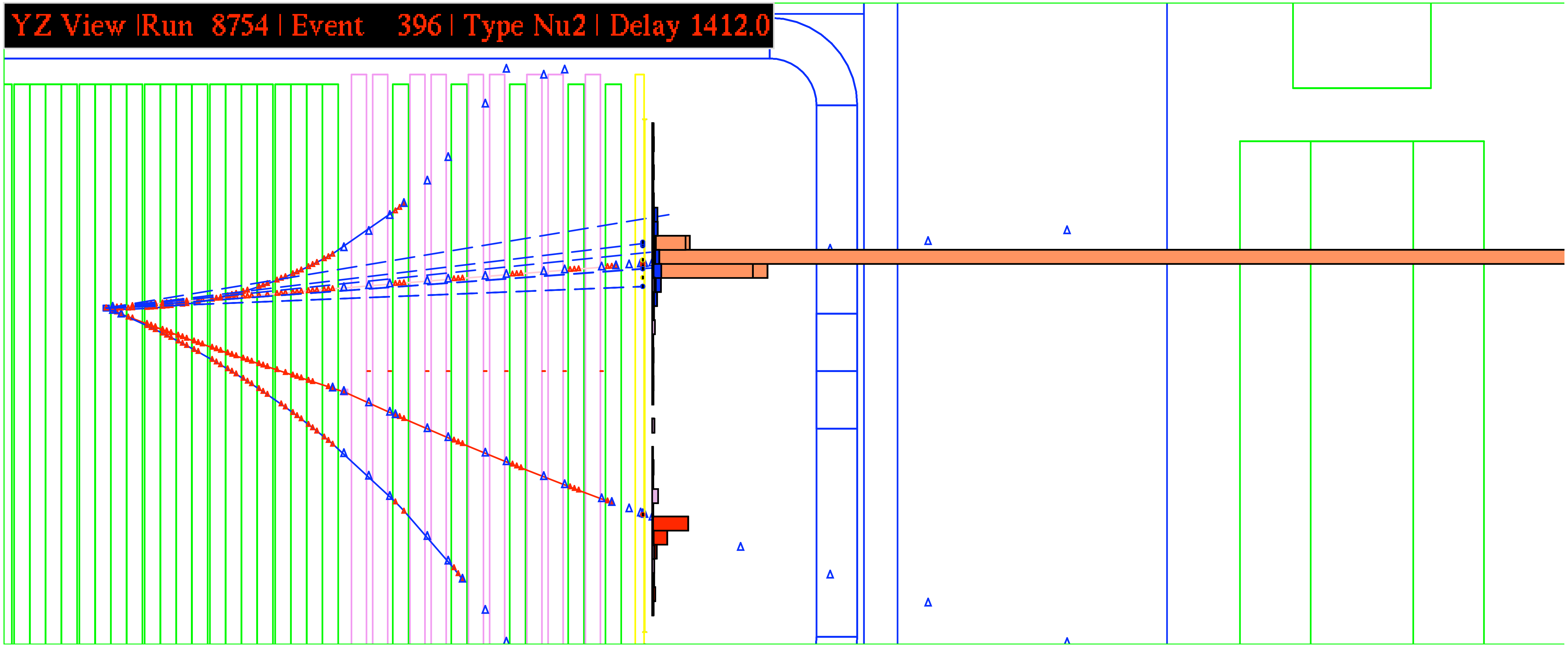
⇒ A must if there are large-Δm^2 oscillations

- Measurement of absolute flux

- To discover δ_{CP} we ought to ensure that ν_e & anti-ν_e events are as expected

⇛ *ND must measure* π^0 *and* ν_e & *anti*-ν_e ➧ *e- -vs- e+*

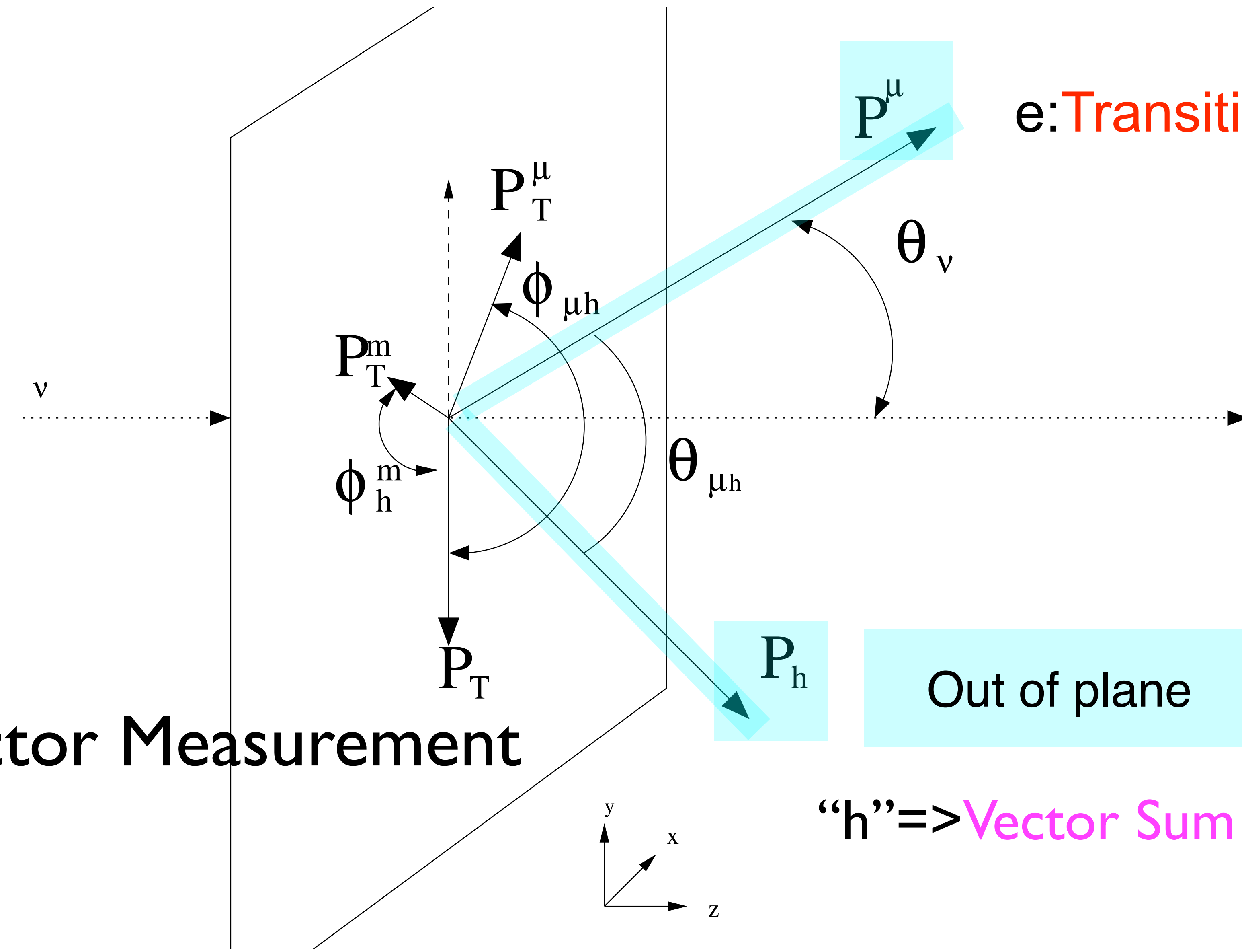
A $\bar{\nu}_e$ CC candidate in NOMAD



- x12 higher sampling in STT (HiResMnu)
- x4π calorimetric and μ converage

Kinematics in STT

USC HEP
University of South Carolina
High Energy Physics



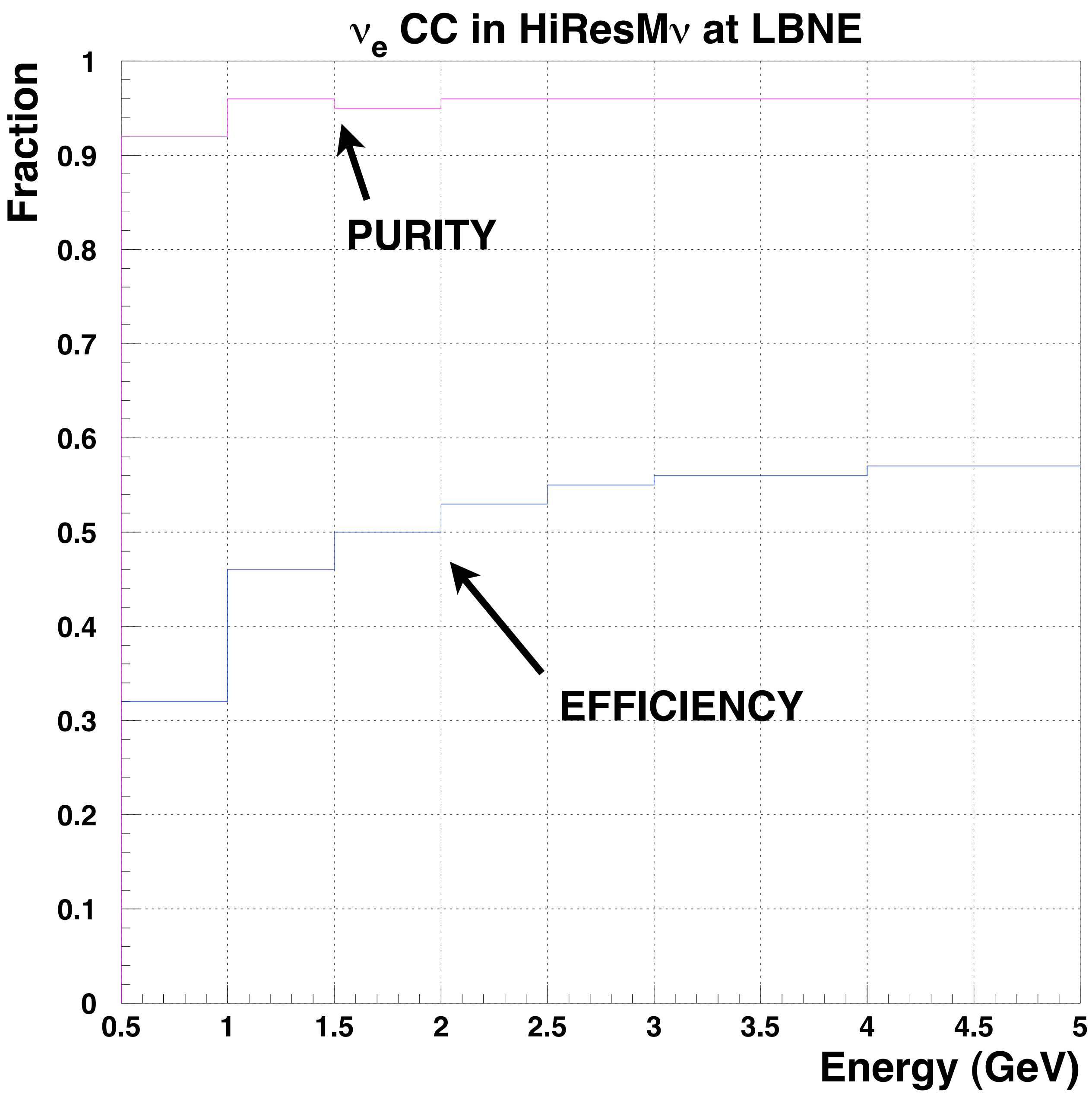
e:Transition Radiation

Out of plane

⇛ Pt-Vector Measurement

“h”=>Vector Sum of Tracks

IDENTIFICATION OF ν_e CC INTERACTIONS



- *The HiResMν detector can distinguish electrons from positrons in STT*

  $\Longrightarrow$ *Reconstruction of the e's as bending tracks NOT showers*

- *Electron identification against charged hadrons from both TR and dE/dx*

  $\Longrightarrow$ *TR π rejection of 10^{-3} for $\varepsilon \sim 90\%$*

- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject non-prompt backgrounds (π^0 in ν_μ CC and NC)*

  $\Longrightarrow$ *On average $\varepsilon =$ 55% and $\eta =$ 99% for ν_e CC at LBNE*

VeBar-CC Sensitivity:

If we keep the signal efficiency at ~55%, then purity is about 95%

Absolute Flux using ν-e Elastic NC Scattering

ॐ Using the Weak Mixing Angle (0.238) at Q~0.1 GeV (known to ≤1% precision)

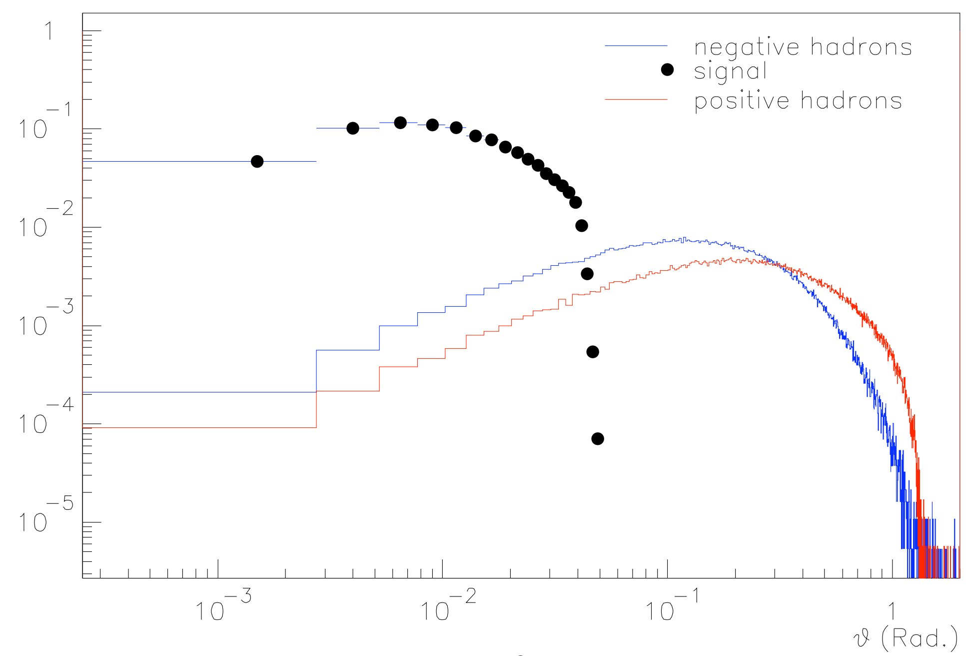
⇒ $\sigma(\nu_x e\text{-NC})$ known ⇒ Absolute-$\phi(\nu_x)$

ॐ ν-e ➽ Signal: Single, forward e-
Background: NC induced π^0 ➽ γ ➽ e- (e+ invisible): charge-symmetric

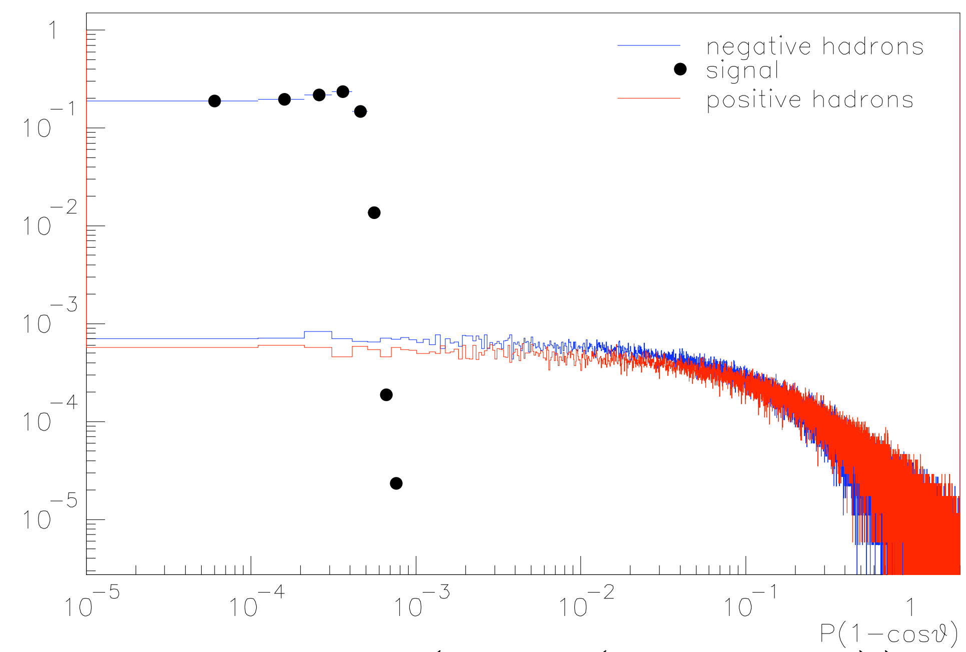
ॐ Two-step Analysis: ✹Electron-ID: TR ✹Kinematic cut: ζ=Pe(1-cosΘe)

Simulation of charged hadron background.

(use LBNE Flux)



θ



$\zeta\ (\equiv P_e(1-\cos\theta))$

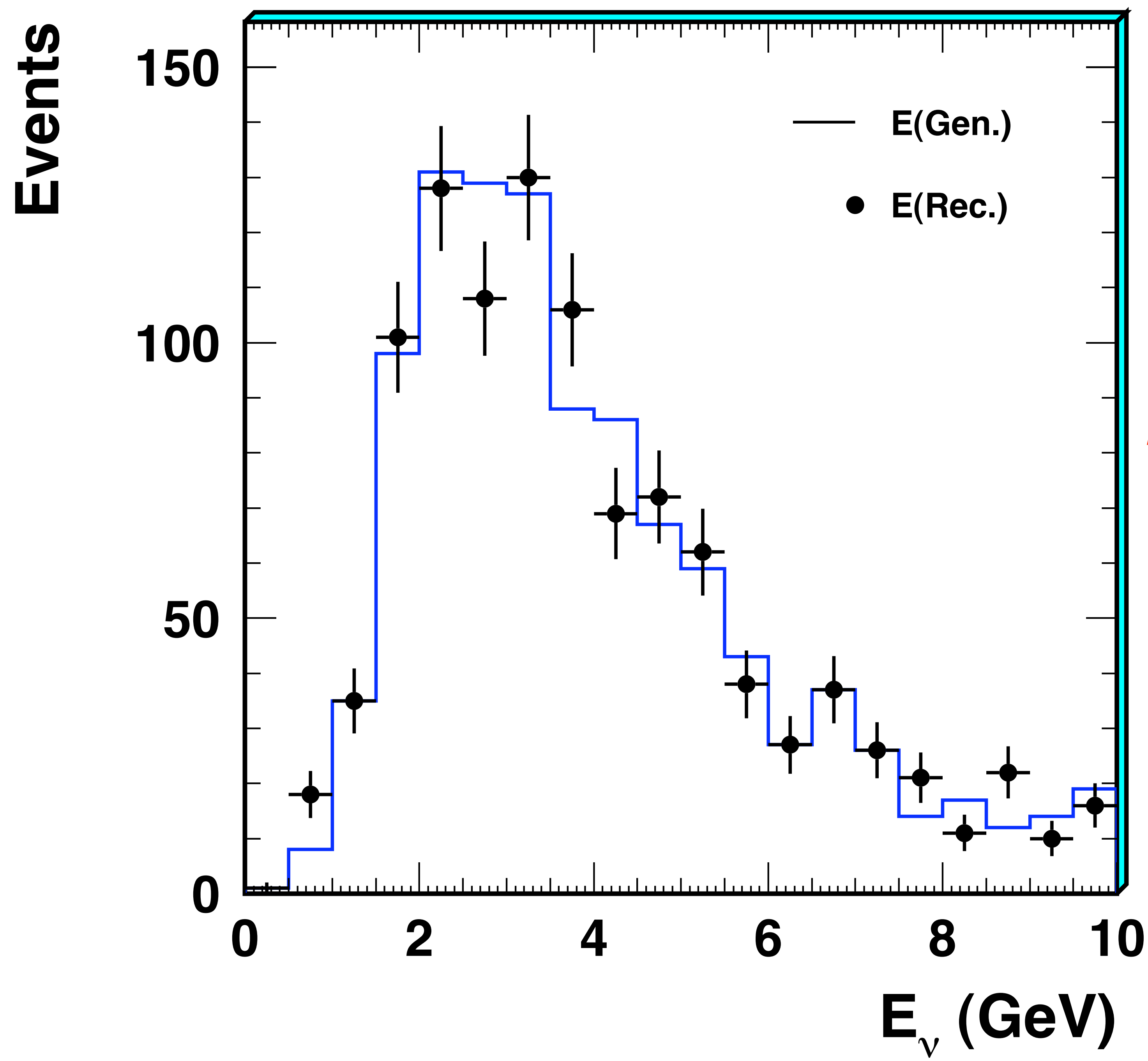
Background charge symmetric & benign

Eff➢64%
Bkg➢ ≤10**(-6) ⇚ Measured

⇚ Conclusion

Absolute Flux using ν-e Elastic Scattering

- Shape of Enu using (E_e, θ_e):
- The precision on relative ν-flux (shape) is worse than in that determined using Low-ν0 technique

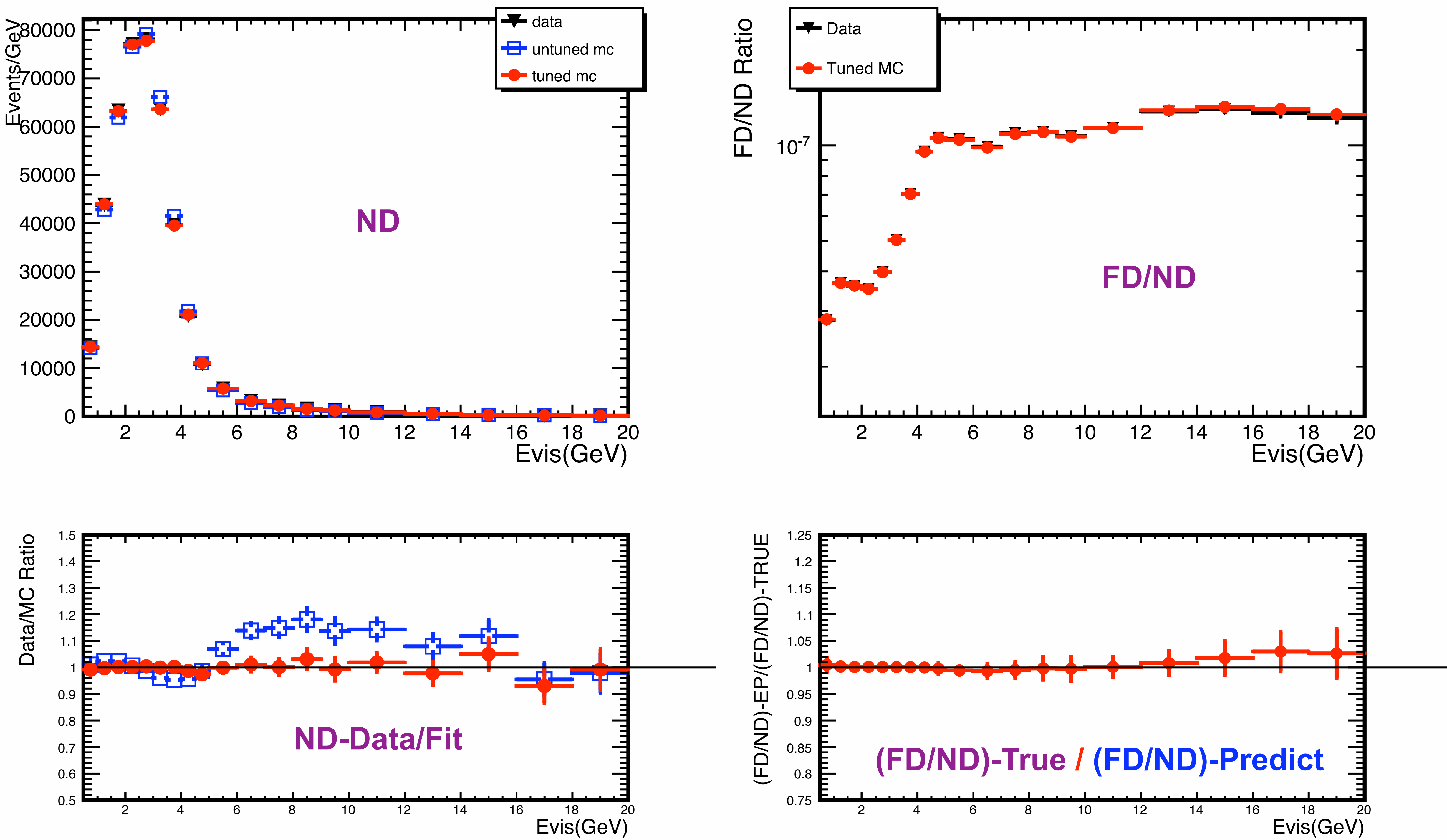


1<Enu<4 => 1000 events
700kW; 3Yr Nu-Run

⇛ *ND will provide ~3% precision on Absolute-ν_μ*

Shape of νμ or Anti-νμ Flux using Low-ν0 Method

ν_μ, **Low-Nu0 Fit, ND at 500m** Relative **ν**μ-Flux Measurement using Low-ν0 @ LBNE



Conclusion ⇛
Predict FD/ND flux-ratio with high precision

π0-Reconstruction

- Clean π0- and γ-signatures in HiResMnu(STT)

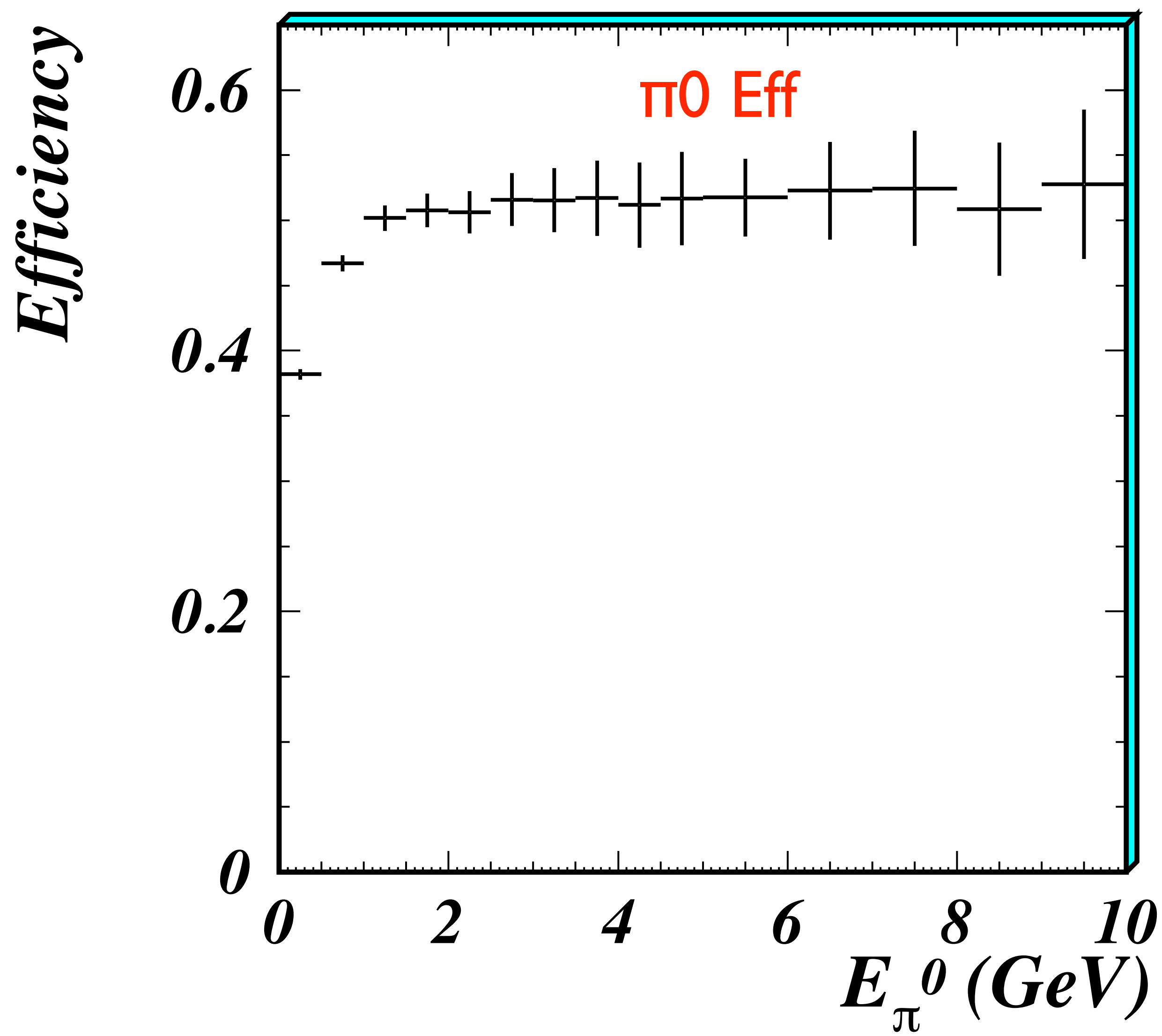
- ν-NC & CC ➻ π0 ➻ γγ

~50% of the γ ➻ e+e- will convert in the STT, away from the primary vertex. We focus on these

- γ-Identification:
  - e-/e+ ID:TR
  - Kinematic cut: Mass, Opening angle

➢ At least one converted γ in STT (Reconstructed e- & e+; e- or e+ traverse ≥6 Mods)

➢ Another γ in the Downstream & Side ECAL



Conclusion ⇛

π0's Very well constrained in CC and NC

MEASUREMENT OF THE RATIO $\mathcal{R}_{e\mu}$ ⇐*Search/Impact of Large-Δm**2 Oscillation*

- *Independent analysis of neutrino data and anti-neutrino data due to possible differences following MiniBooNE/LSND results*

  $\Longrightarrow$ *Need a near detector which can identify e^+ from e^-*

- *Measure the ratio between the observed $\nu_e(\bar{\nu}_e)$ CC events and the observed $\nu_\mu(\bar{\nu}_\mu)$ CC events as a function of L/E_ν:*

$$\mathcal{R}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \nu_e N \to e^- X}{\#\ of\ \nu_\mu N \to \mu^- X}(L/(E\nu))$$

$$\bar{\mathcal{R}}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \bar{\nu}_e N \to e^+ X}{\#\ of\ \bar{\nu}_\mu N \to \mu^+ X}(L/(E\nu))$$

- *Compare the measured ratios $\mathcal{R}_{e\mu}(L/$ Eν *and* $\bar{\mathcal{R}}_{e\mu}(L/$ Eν *with the predictions from the low-ν_0 flux determination assuming no oscillations* ⇐ Benefit from External K+/π+, K-/π-, K0L/K+

- *Same analysis technique used in NOMAD to search for $\nu_\mu \to \nu_e$ oscillations.*

ainment of the events so reducing the usable statistics.

Measurement	STT	Sci+μDet	LAr	LArB	LArB+Sci+μDet	LAr+STT
In Situ Flux Measurements for LBL:						
$\nu e^- \to \nu e^-$	Yes	No	Yes	No	No	Yes
$\nu_\mu e^- \to \mu^- \nu_e$	Yes	Yes	No	Yes	Yes	Yes
$\nu_\mu n \to \mu^- p$ at $Q^2 = 0$	Yes	Yes	No	No	Yes	Yes
Low-ν_0 method	Yes	Yes	No	Yes	Yes	Yes
ν_e and $\bar{\nu}_e$ CC	Yes	No	No	Yes	Yes	Yes
Background Measurements for LBL:						
NC cross sections	Yes	Yes	No	Yes	Yes	Yes
π^0/γ in NC and CC	Yes	Yes	Yes	Yes	Yes	Yes
μ decays of $\pi^\pm, K^\pm$	Yes	No	No	Yes	Yes	Yes
(Semi)-Exclusive processes	Yes	Yes	Yes	Yes	Yes	Yes
Precision Measurements of Neutrino Interactions:						
$\sin^2\theta_W$ ν N DIS	Yes	No	No	No	No	Yes
$\sin^2\theta_W$ νe	Yes	No	Yes	No	No	Yes
Δs	Yes	Yes	Yes	Yes	Yes	Yes
νMSM neutral leptons	Yes	Yes	Yes	Yes	Yes	Yes
High Δm^2 oscillations	Yes	No	No	Yes	Yes	Yes
Adler sum rule	Yes	No	No	No	No	Yes
$D/(p+n)$	Yes	No	No	No	No	Yes
Nucleon structure	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE XXVIII: Summary of measurements that can be performed by different ND reference configurations.

Summary page from the Short-Baseline Physics Report: Roberto Petti

Synergy between the ND-Design for LBNE and Nu-Factory

- A small group actively working on the ND-design for the Nu-Factory
- Although the Nu-Factory beam ($\mu \rightarrow \nu_e \, \nu_\mu$) simpler than LBNE, the requirements on systematic precision are much higher
- The LBNE-STT (HIRESMNU) is one of the candidates under consideration

$\Rightarrow$ *Joint effort will benefit all*

Outlook

- An ambitious ν program at Fermilab

- The LBNE-ND aims to provide precise constraints on the systematic errors affecting the ν oscillation physics:
  - ⇒ Flux of ν_e, ν_μ & Anti-(ν_e, ν_μ)
  - ⇒ Absolute $E\nu$-scale
  - ⇒ Measurement of $\pi^{0/+/-}$ --- backgrounds to oscillation-signal --- in NC and CC
  - ⇒ Difference between ν & Anti-(ν) interactions

- A rich short-baseline ν-physics

- We welcome, *and need*, new institutions/collaborators

Backup Slides

PHYSICAL REVIEW C **82**, 044601 (2010)

Pionic correlations and meson-exchange currents in two-particle emission induced by electron scattering

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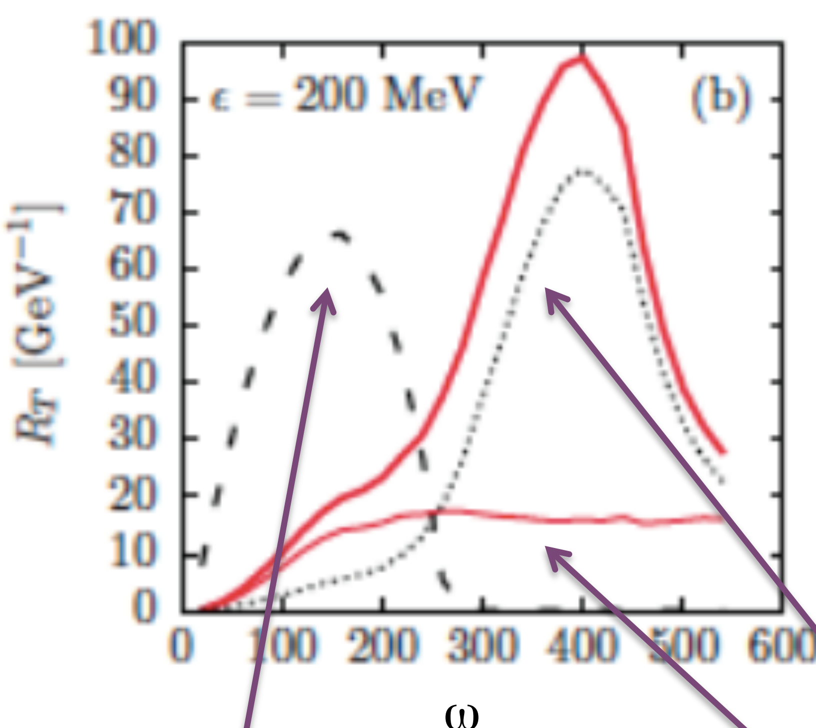


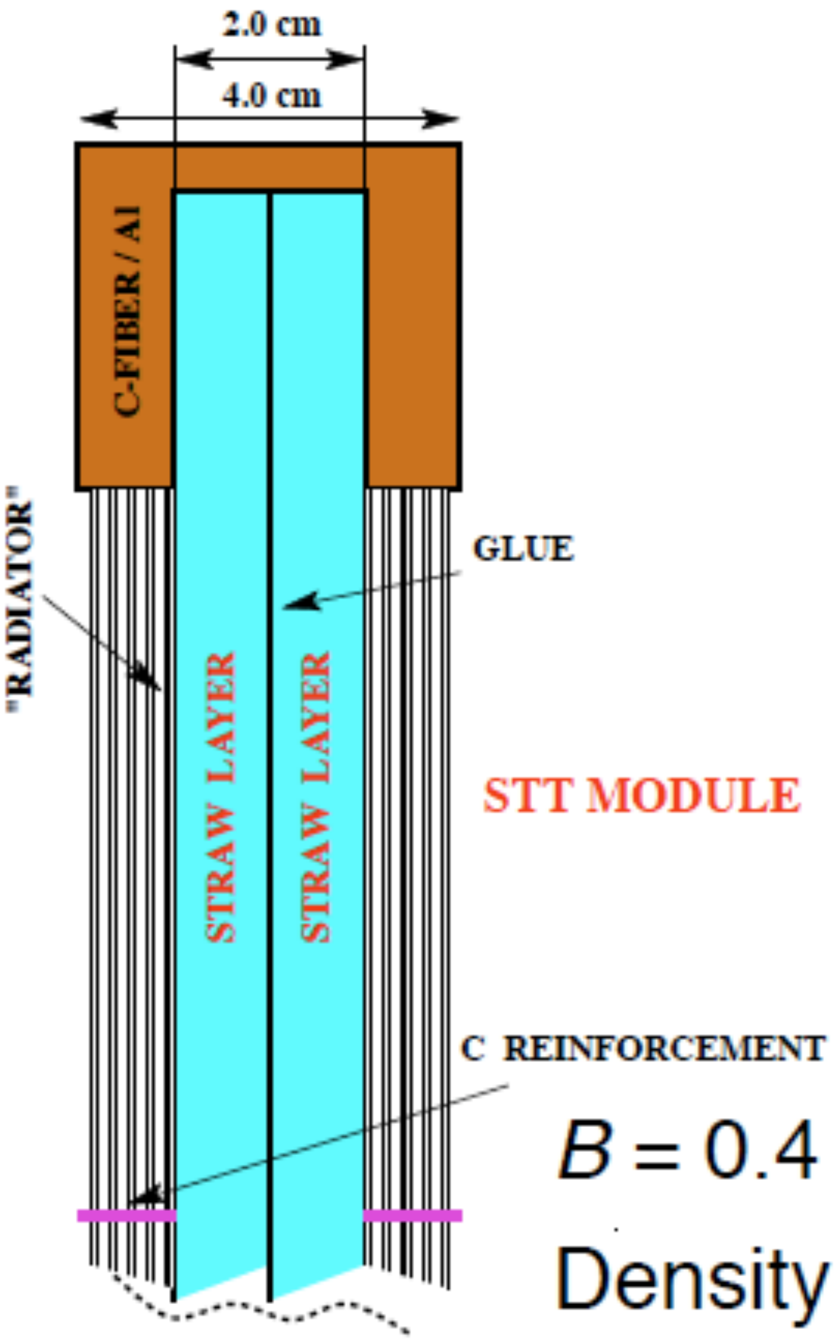
One body RFG

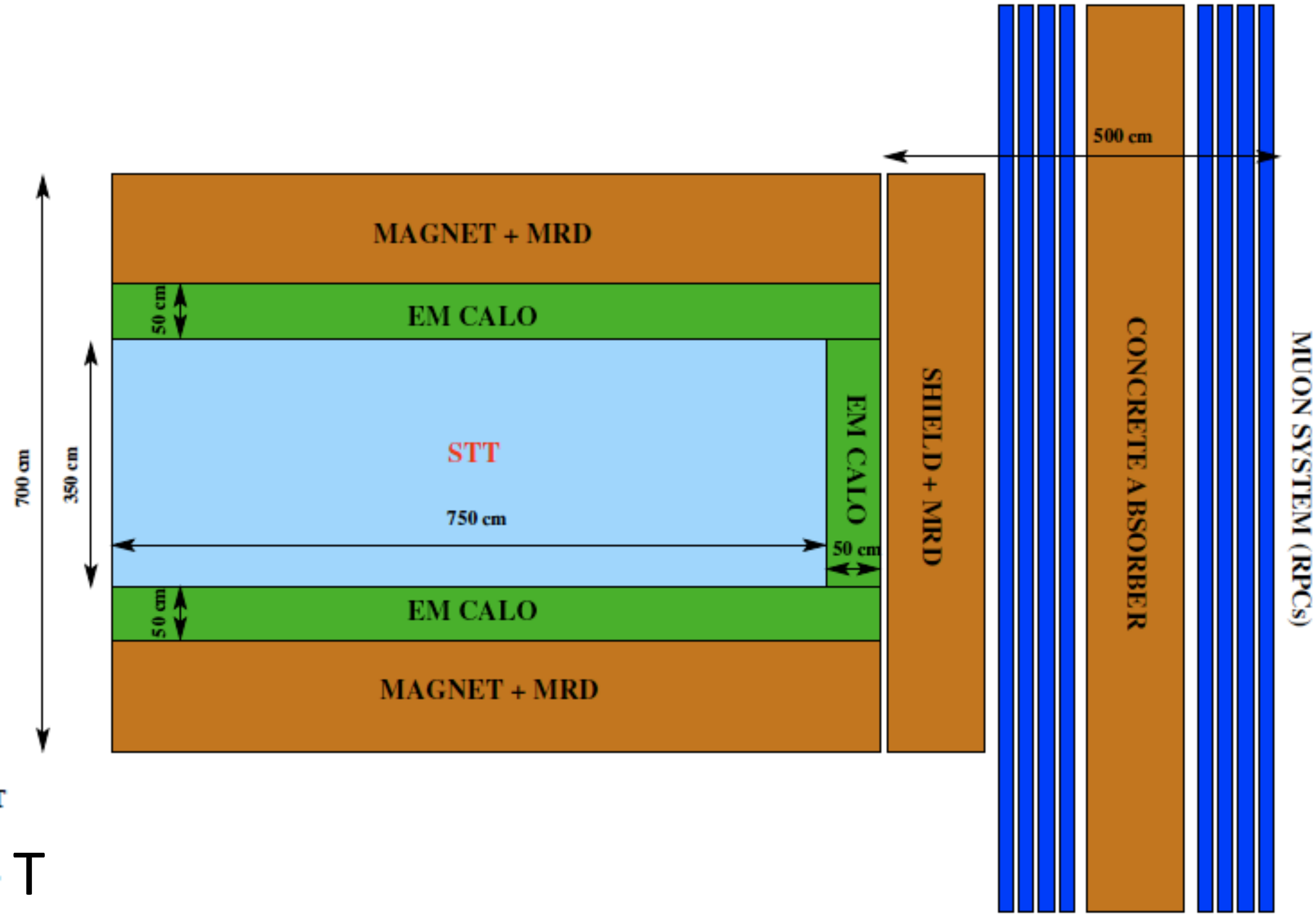
Meson exchange

Correlation

Meson-Exchange Currents predict a much larger fraction of the incident neutrino energy going into the hadron sector. Neutrino & antineutrino interactions may have different energy corrections up to ~300MeV and may create a spurious "CP-violating" effect, especially at 1.5 GeV where the sensitivity is maximum.

R_T = transverse response function





$B = 0.4$ T

Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ⤀ e-/e+ ID ⇒ γ (w. Kinematics)

dE/dx ⤀ Proton, π+/-, K+/- ID

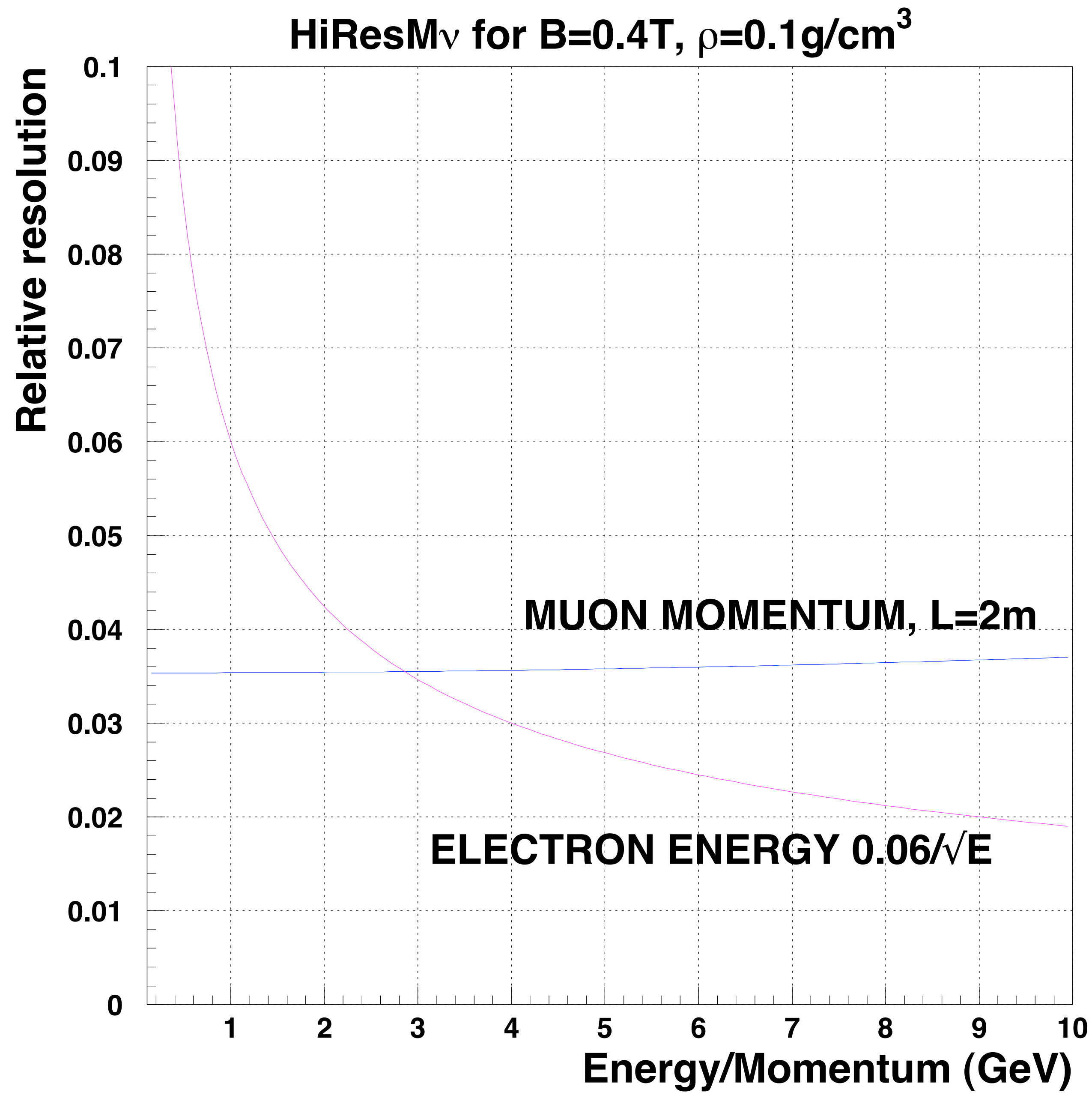
Magnet/Muon Detector ⤀ μ+/-

Resolutions in HiResMnu

- $\rho \simeq$ 0.1gm/cm^3
- Space point position $\simeq$ 200μ
- Time resolution $\simeq$ 1ns

- CC-Events Vertex: Δ(X,Y,Z) $\simeq$ *O*(100μ)
- Energy in Downstream-ECAL $\simeq$ 6%/√E
- μ-Angle resolution (~5 GeV) $\simeq$ *O*(1 mrad)

- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%

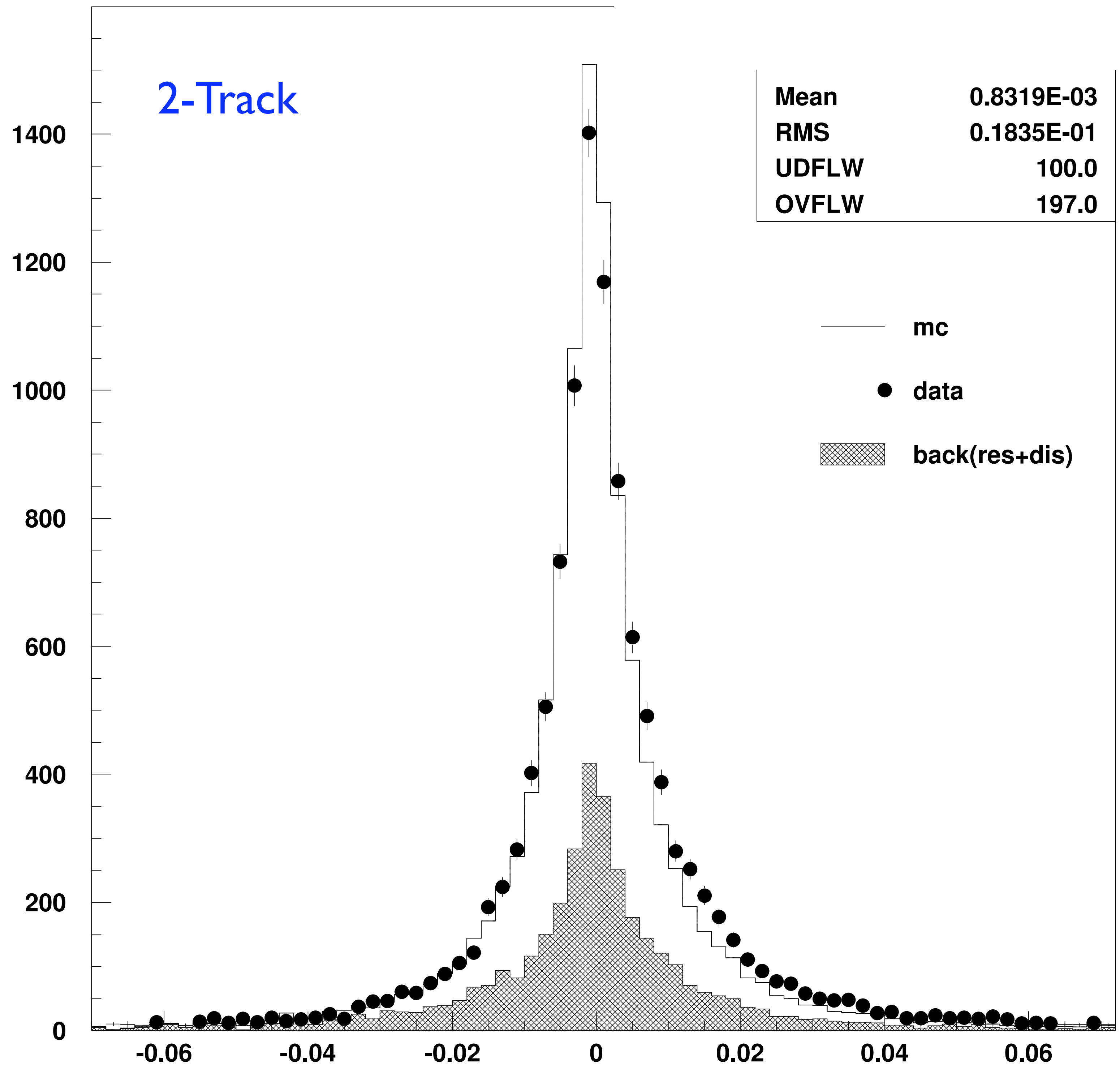


Sensitivity Calculations:

- Parametrized calculation
- Repeat with NOMAD configuration and checked against the Data and Geant-MC (Agree within 15%): ReWt

Detector Performance

	MicroBooNE	Small Magnetized LAr	STT	Scintillator Tracker
Fiducial Volume	70 T	20 T	7 T	3 T
Vertex Res.	1 mm	1 mm	0.1 mm	3 mm
Angular Res.	10 mrad	10 mrad	2 mrad	10 mrad
E_e Res.	10%	10%	3.5%	10%
E_μ Res.	10%	10%	$6\%/\sqrt{E}$	10%
$\nu_\mu / \bar{\nu}_\mu$ ID	No	Yes	Yes	Yes
$\nu_e / \bar{\nu}_e$ ID	No	Yes (E<1.5 GeV)	Yes	No
$NC\pi^0/CCe$ Rej.	1%	1%	0.1%	1%
$NC\gamma/CCe$ Rej.	1%	1%	0.2%	1%
$CC\mu/CCe$ Rej.	0.1%	0.1%	0.01%	0.1%



{Evis(2-Trak) - Enu(1-Trk w. PFermi=0)} / [Evis(2-Trak)]

⇒ *constraint on Eν Scale*

Flux: … Always the Flux

ༀ *Inverse Muon Decay*: $\nu_x + e^- \twoheadrightarrow \nu_x + \mu^-$ {Single, forward μ^-}

- ν_μ (t-channel) or Anti-ν_e (s-channel)
- Elegant, Simple but steep threshold (calculable), $E_\nu \geq 11$ GeV
- Systematic Advantage of STT lies in reducing systematic errors incurred by CCFR or CHARM-II in extrapolating the background to the signal $\zeta = P_e(1-\cos\Theta_e) \leq$ Cut

ༀ ν-*Electron Elastic Events*: $\nu_x + e^- \twoheadrightarrow \nu_x + e^-$ {Single, forward e^-}

- Different processes: $\nu_e e$-CC, Anti-$\nu_e e$-CC, & all flavor $\nu_x e$-NC
- Different E_e spectrum
- Focus on $\nu_\mu e$-NC: Experimentally the most challenging

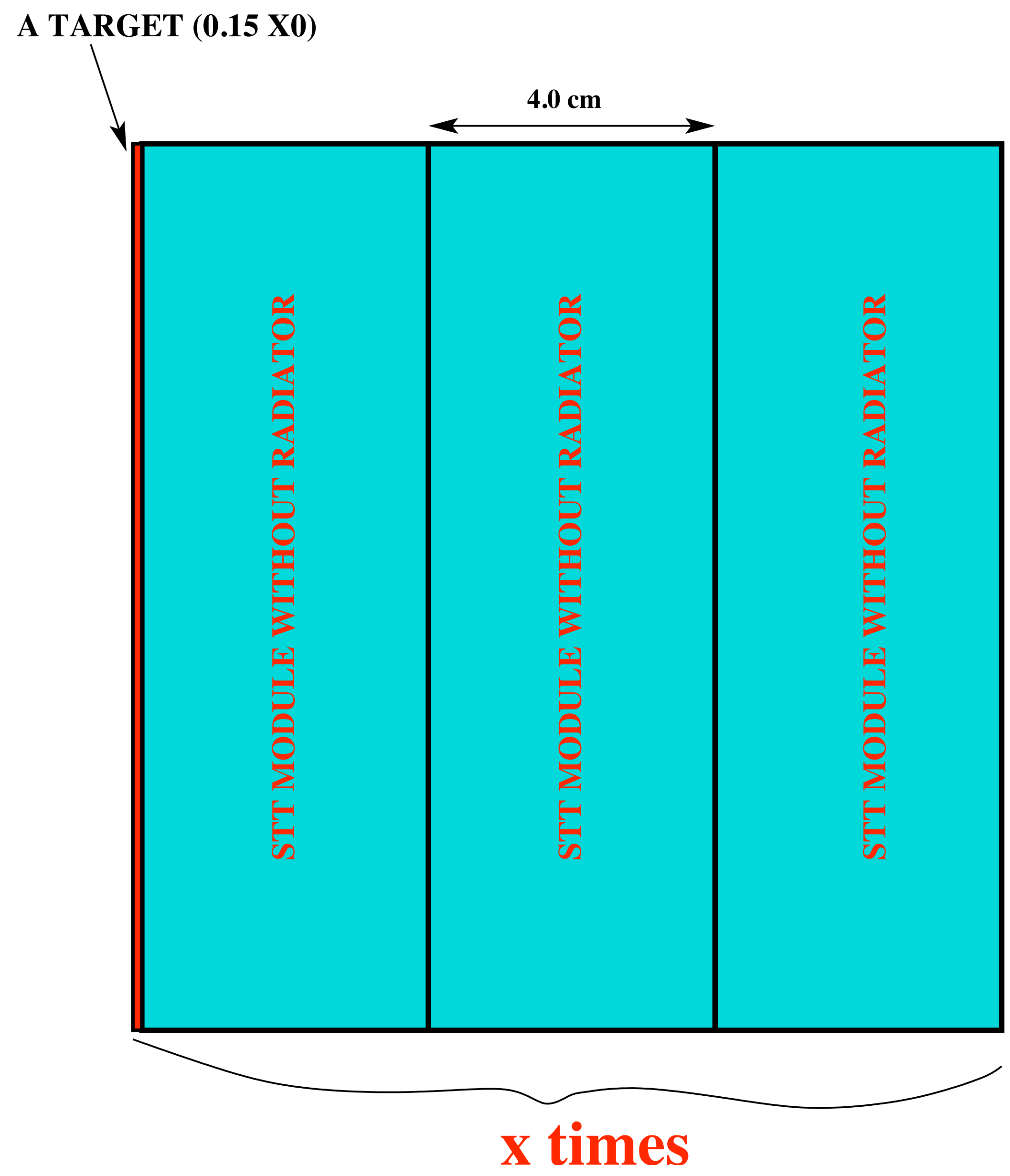
✺ The Weak Mixing Angle (0.238) at Q~0.1 GeV is known to ≤1% precision

$\Rightarrow \sigma(\nu_x e\text{-NC})$ known $\Rightarrow$ Absolute-$\phi(\nu_x)$

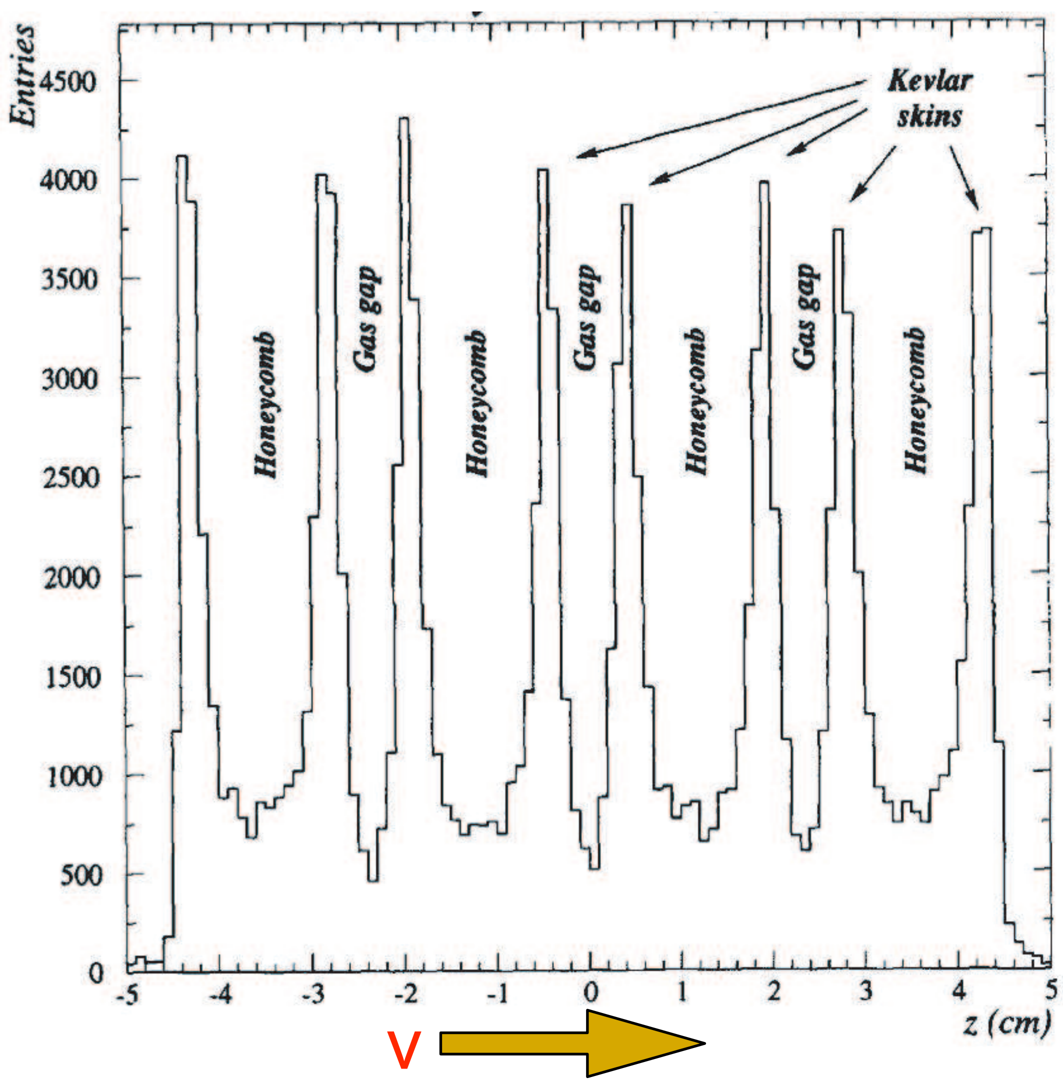
MEASURING NUCLEAR EFFECTS *(Water, Ar, ..)*

- *Measure the A dependence (Ca, Cu, H_2O, etc.) in addition to the main C target in STT:*
  - *Ratios of F_2 AND xF_3 on different nuclei;*
  - *Comparisons with charged leptons.*

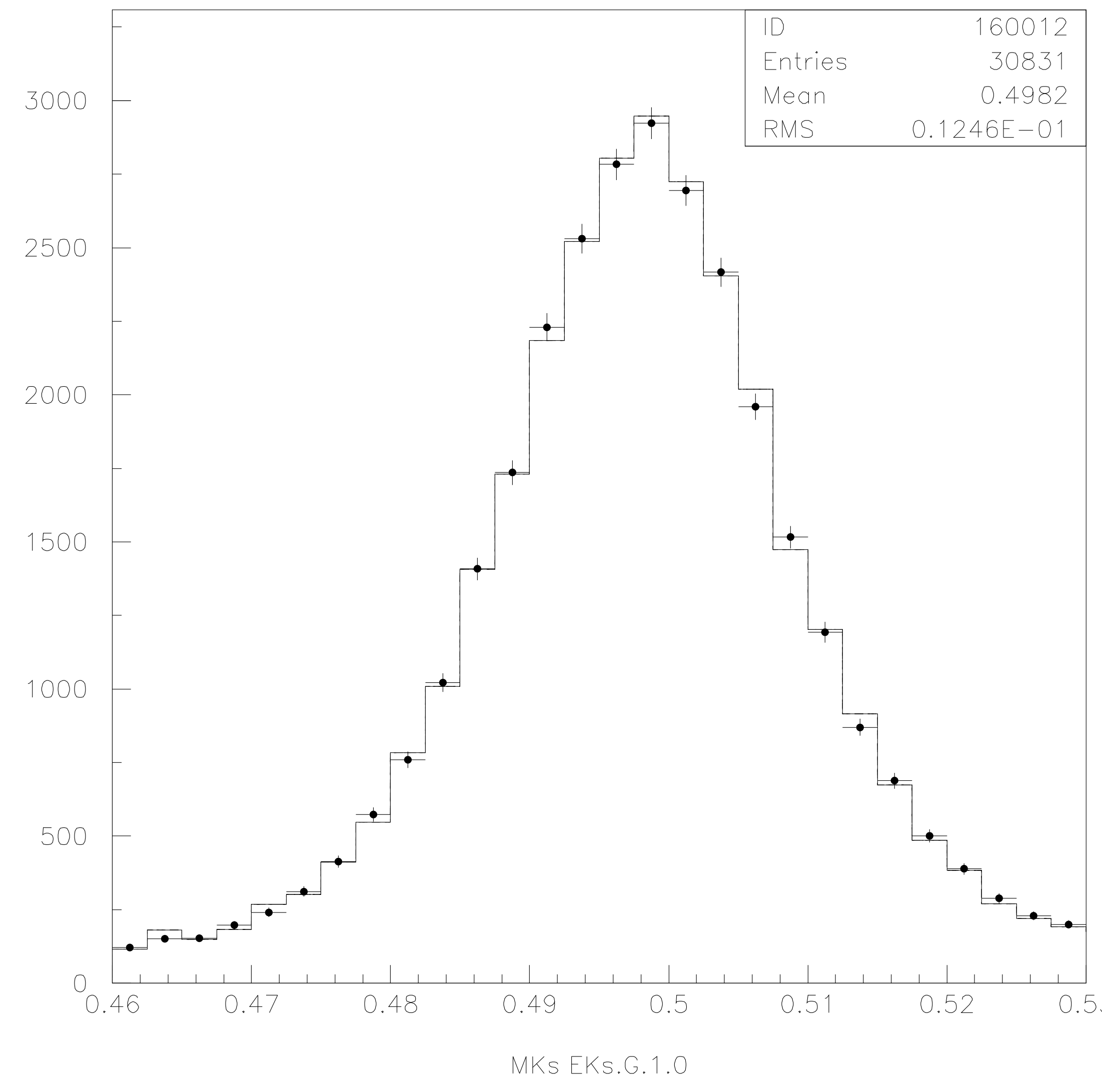
- *Use 0.15X_0 thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.*
  - *For Ca target consider $CaCO_3$ or other compounds;*
  - $\boxed{\text{OPTION}}$*: possible to install other materials (Pb, etc.).*



What we build on: NOMAD DATA



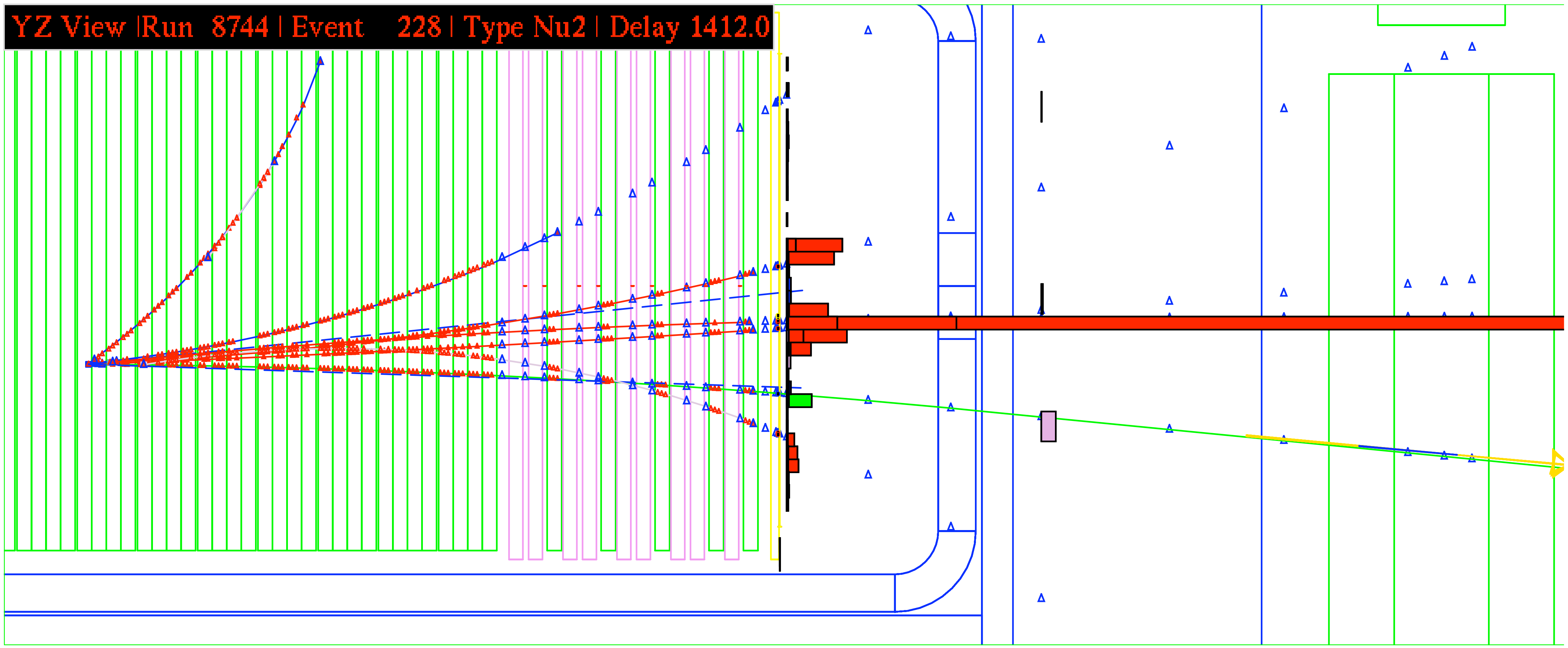
Neutrino radiography of one drift chamber



Reconstructed K^0 mass

- ✦ *NOMAD: charged track momentum scale known to* $< 0.2\%$
  hardonic energy scale known to $< 0.5\%$
- ✦ *HiResMν:* $\boxed{200\times}$ *more statistics and* $\boxed{12\times}$ *higher segmentation*

A ν_μ CC candidate in NOMAD



LOW-ν_0 METHOD ⇐Shape of νμ or Anti-νμ Flux

✦ *Relative flux vs. energy from low-ν_0 method:*

$$N(E_\nu : E_{\mathrm{HAD}} < \nu^0) = C\Phi(E_\nu) f(\frac{\nu^0}{E_\nu})$$

the correction factor $f(\nu^0/E_\nu) \to 1$ for $\nu^0 \to 0$.

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low ν values*

✦ *Fit Near Detector $\nu_\mu, \bar{\nu}_\mu$ spectra:*

- *Trace secondaries through beam-elements, decay;*
- *Predict $\nu_\mu, \bar{\nu}_\mu$ flux by folding experiental acceptance;*
- *Compare predicted to measured spectra $\Longrightarrow \chi^2$ minimization*

$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F) g(P_T) h(x_F, P_T)$$

- *Functional form constraint allows flux prediction close to $E_\nu \sim \nu^0$.*

✦ *Add measurements of $\pi^\pm/K^\pm$ ratios from hadro-production experiments to the empirical fit of the neutrino spectra in the Near Detector*

Systematic-Errors in Low-$\nu 0$ Relative Flux: ν_μ & Anti-ν_μ

- Variation in $\nu 0$-cut
- Variation in $\nu 0$-correction
- Systematic shift in Ehad-scale
- Vary σ(QE) ±10%
- Vary σ(Res) ±10%
- Vary σ(DIS) ±10%
- Vary functional-forms
- Systematic shift in Emu-scale

- Beam-Transport (ND at 1000m)

Includes:

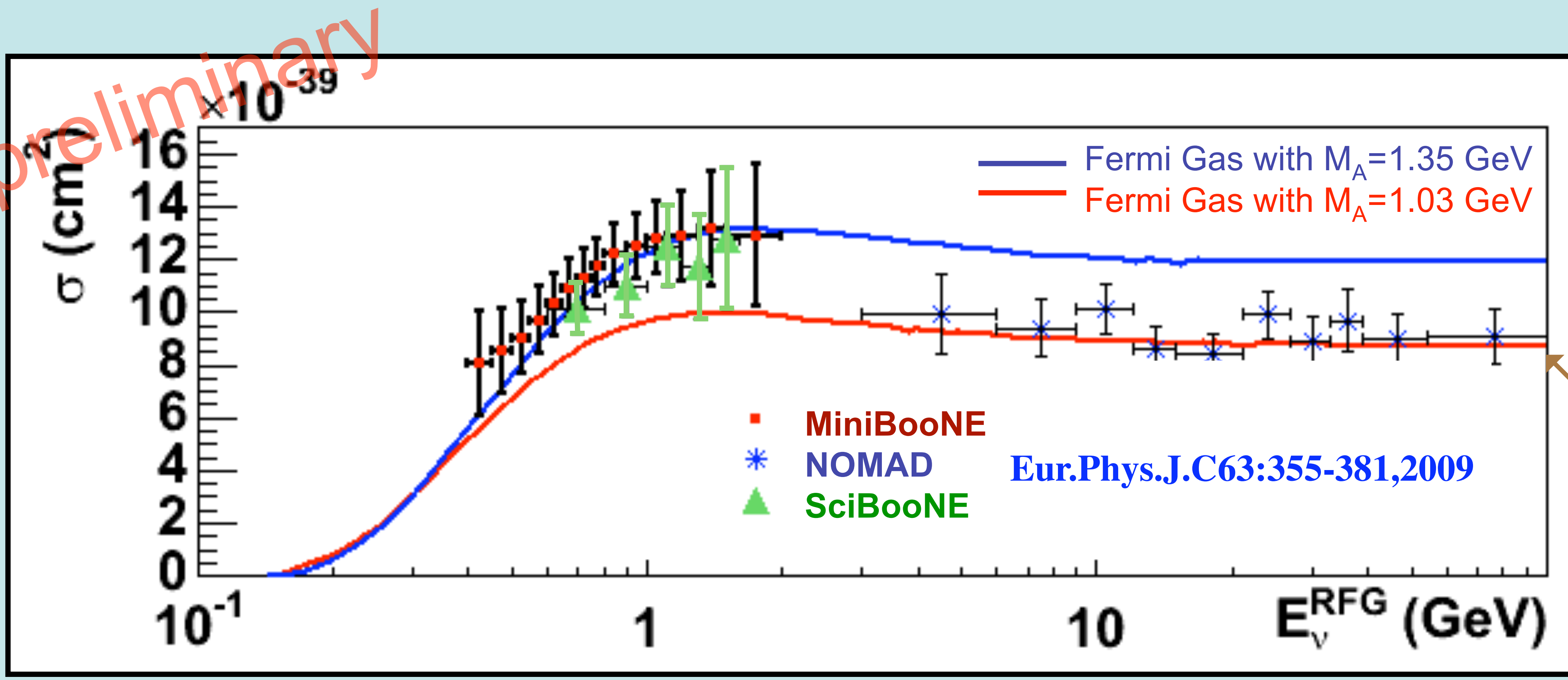
*Alignment (1.0mm)
*Horn Current (0.5%)
*Inert material (0.25λ)
*Proton spot size

⇒ Revisit these (?) & Investigate ND @ 500m

QE

Quasi-Elastic Scattering

- new, modern measurements of QE σ at these energies (on ^{12}C)



(T. Katori, NuInt09)

Discrepancy?

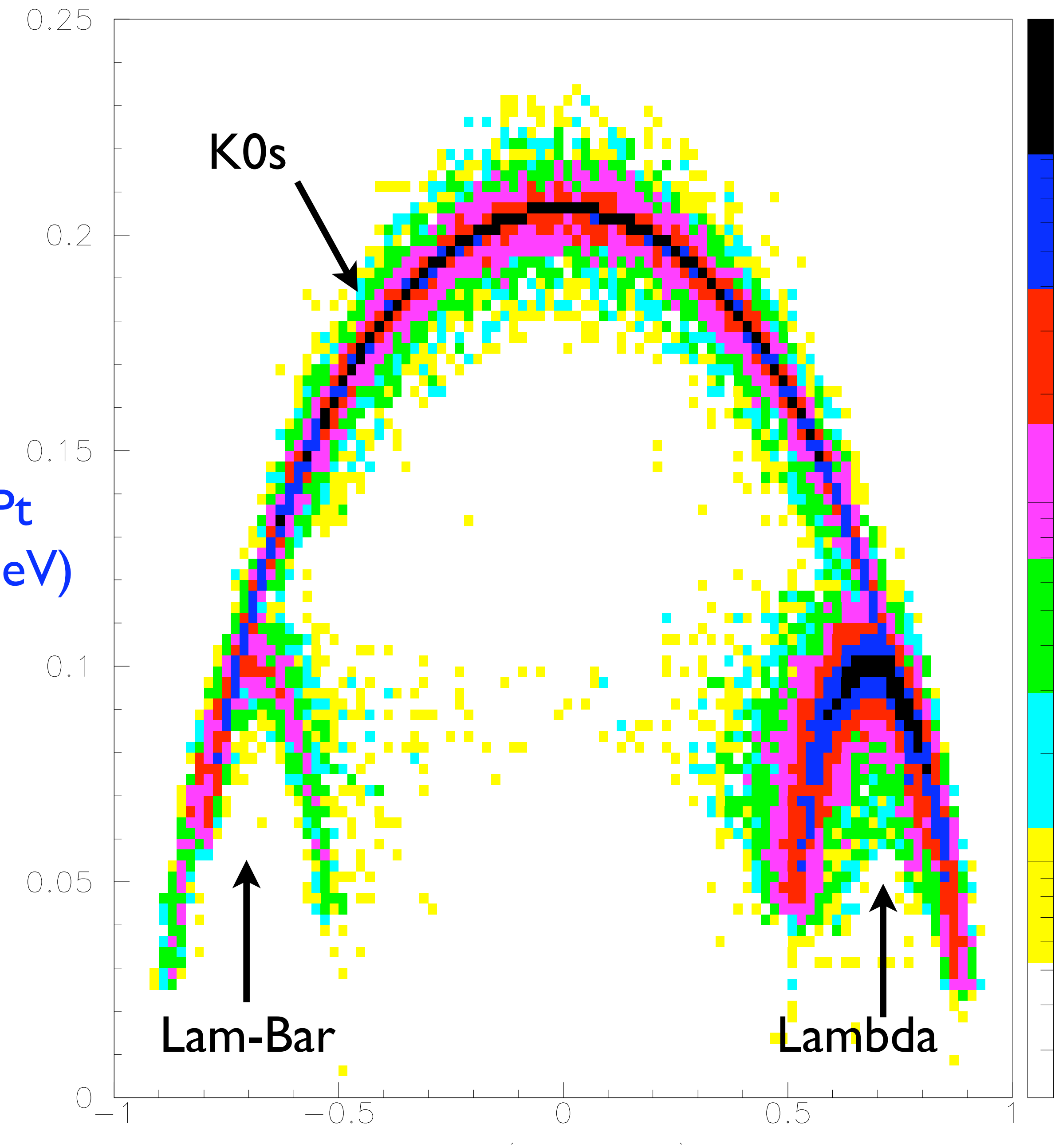
~ 30% difference between QE σ measured at low & high E on ^{12}C ?!

?

Measurement of exclusive topologies

- High resolution allows excellent reconstruction of exclusive decay modes
- NOMAD performed detailed analysis of strange particle production: $\Lambda, \bar{\Lambda}$
- Δ resonances in CC & NC are easier to reconstruct
- Constraints on NC decay mode $\Delta \rightarrow N\gamma$

CC-Data: Armenteros Plot



Lambda → Calibration of Proton Reconstruction